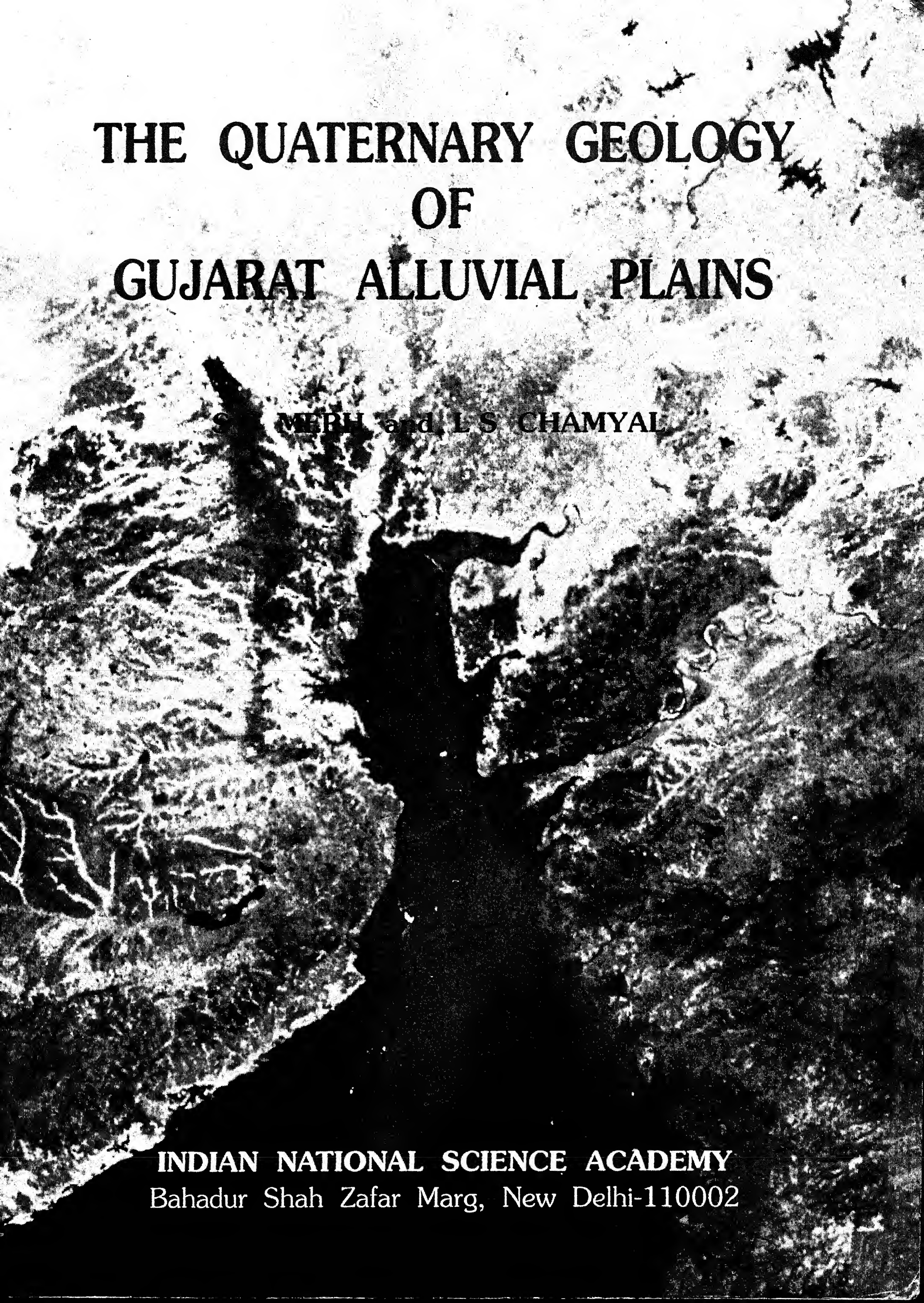
THE QUATERNARY GEOLOGY OF GUJARAT ALLUVIAL PLAINS



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FOREWORD

The Quaternary geological studies started receiving attention in this country only since a few decades back, but its importance is now being realised by a large section of earth scientists. The diversity in the terrain types that we have in India, are best suited for Quaternary researches. The Earth Scientists from India and abroad have been investigating the Quaternary deposits of our sub-continent, and are engaged in studying the diverse aspects of the Quaternary period, including stratigraphy, sea level changes, palaeoclimates, deserts, neotectonism, drainage and landscape evolution.

This review which is nearly a monograph comprises the details of the investigations carried out on the Quaternary Terrain of Mainland Gujarat. We have described the geological evolution of the area highlighting the control exercised by the factors of palaeoclimate and neotectonism on the succession and processes of Quaternary continental deposition. Commonly referred to as 'Gujarat Alluvial Plains', the thick non-marine succession has preserved within it an interesting record of various tectonism and climate related processes. Investigations pertain mainly on the Upper Quaternary record as revealed in the various river sections, and in this work we have described the details of the stratigraphy, lithology, depositional environments, palaeoclimatic changes and the role of tectonism. Our is more or less an omnibus study wherein we have endeavoured to reconstruct a reasonably dependable sequential stratigraphy correlating the successive formations encountered in the exposed sections, thereby working out a chronology of depositional events under varying environments, periods of non-deposition and sub-aerial weathering, and the influence of tectonism at all stages of deposition. We were assisted by V Sridhar, J Malik and A Khadkikar in our investigations, and to these young research workers goes the credit of providing important and vital data in respect of geomorphology, stratigraphy and lithology, landscape, drainage characteristics, depositional environments and processes.

We are indebted to Dr R K Pant (Ahmedabad) for making us interested in the subject by highlighting the importance and scope of investigations. We considerably benefited by interacting with Prof K S Valdiya (Bangalore), Prof I B Singh (Lucknow), Prof S K Tandon (Delhi) and Prof S N Rajaguru (Pune) in our studies.

S S Merh
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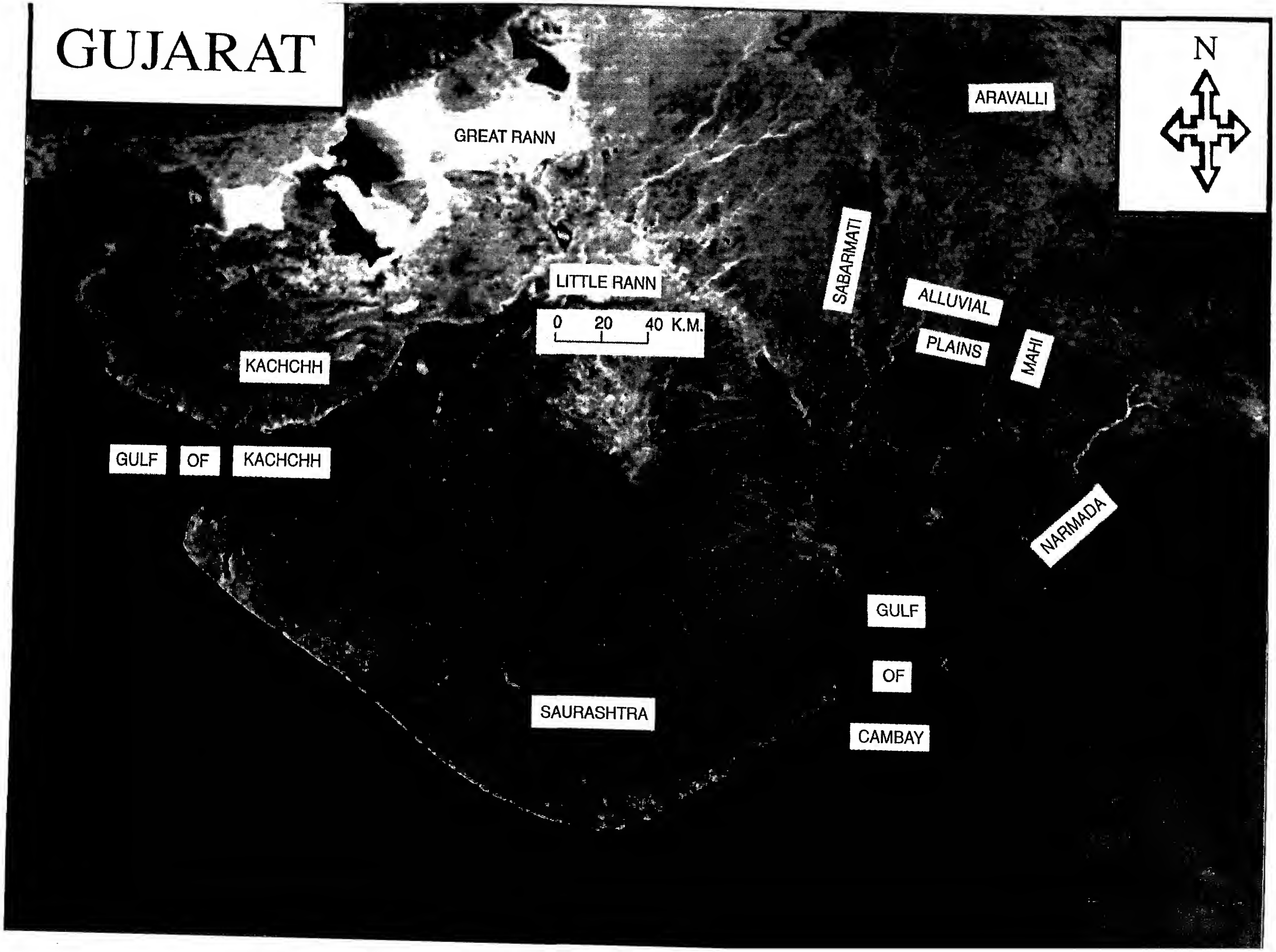
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GREAT RANN
LITTLE RANN
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SABARMATI
ALLUVIAL
PLAINS
MAHI
KACHCHH
GULF OF KACHCHH
NARMADA
GULF OF CAMBAY
SAURASHTRA

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The Quaternary deposits of Gujarat comprise a huge thickness of continental sediments and are commonly referred to as Gujarat Alluvial Plains. The plains show an array of geomorphic features which are the reflections of the various tectonic, erosional and depositional processes of late Quaternary. Neotectonism has played an important role in the evolution of these plains. The site of the sediment accumulation was the Cambay Basin tectonic depression and the entire deposition was controlled by the factors of neotectonism and palaeoclimate. The deposits dominantly fluvial, owe their origin to a succession of depositional events with intervening periods of non-deposition and subaerial weathering. The fluvial activity synchronised with the wet phases whereas breaks indicate cessation of deposition mainly due to decrease in humidity. Four prominent palaeosol horizons indicating subaerial weathering are recognised. The stratigraphic record is represented by a succession of sediments belonging to three fluvial cycles. Each cycle has its own diagnostic sediments consisting of gravel, sand and silt. The third fluvial is seen to have been abruptly terminated by a sudden onset of a dry climate, and this phase of high aridity was responsible for the accumulation of extensive aeolian deposits, which are recorded all over as a continuous blanket of aeolian silt and sand. This aeolian activity was the manifestation of the major arid phase at the close of the Pleistocene that synchronised with the Last Glacial Maxima (LGM). The present day hummocky and undulatory topography of the plains, shows stabilisation of this aeolian horizon, and points to an increase in humidity, the last major palaeoclimatic event of the Holocene.

The fluvial deposition took place during Upper Quaternary by a drainage system which was quite different from the one seen today. Main bulk of the deposition was brought about by numerous slope controlled rivers that followed ENE-WSW to NE-SW courses and finally impinged into the ancestral Arabian Sea. This early drainage was disrupted and considerably modified during Holocene such that some rivers (Sabarmati and Mahi) started flowing along new courses and others survived only as relicts or as very insignificant streams. This disruption of earlier drainage by superimposition of a new one was entirely a tectonic phenomenon, brought about by development of NNE-SSW fracture zones. This late fracturing took place some time after the deposition and stabilisation of the uppermost aeolian horizon. Correlating the various climatic changes with the global sea levels, attempt has been made to establish a broad chronology of the various events. However, a better and clearer picture will emerge only when precise ages of sediments of successive horizons are available.

Key Words : Quaternary, Tectonism; Depositional Environments; Palaeoclimate; Gujarat Alluvial Plains

Introduction

The states of Gujarat and Rajasthan form an important Quaternary terrain of the Indian subcontinent. The Quaternary sediments occupying large areas in these two States are of marine, fluvial and aeolian origins. The marine deposits are restricted in the coastal areas, fluvio-marine make up the two Ranns of Kachchh and the aeolian counterparts occur in the North Gujarat and S. Rajasthan. However, the Mainland Gujarat comprises a huge thickness of continental sediments of dominantly fluvial origin. These continental deposits constitute the Gujarat alluvial plains (Fig. 1) and have preserved within them an interesting record of the various tectonic and climatic changes.

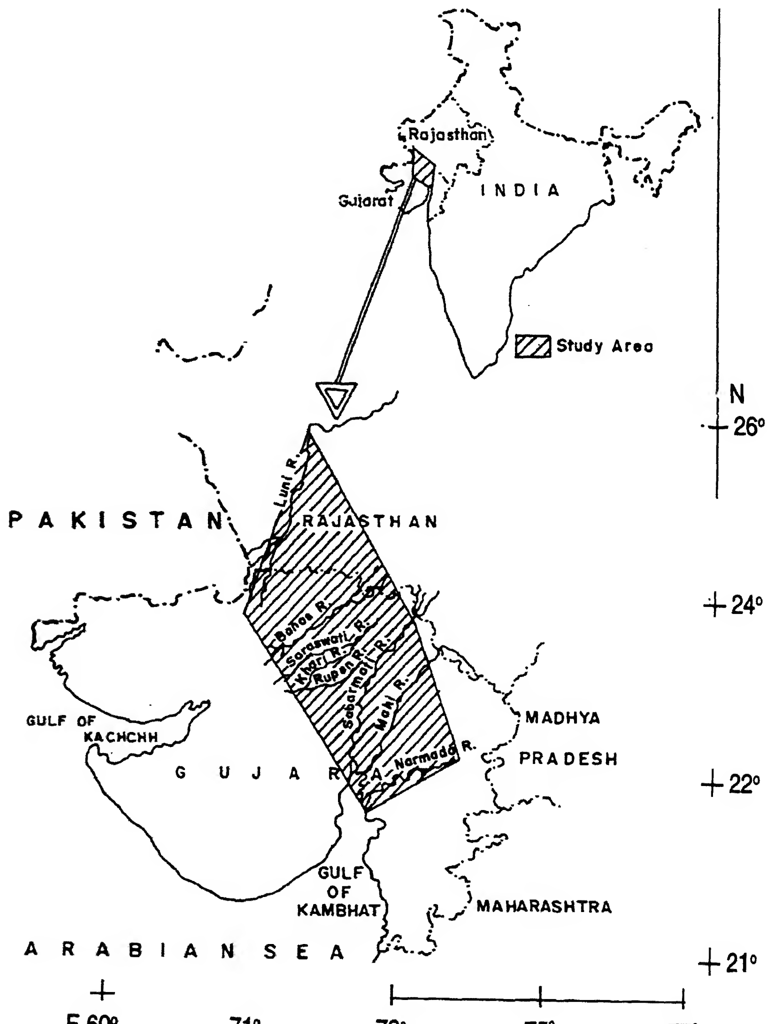


Fig.1 Location map, shaded area shows the extent of alluvial plains

The Mainland Gujarat is further divisible into two well-defined zones: *(i)* the Eastern Rocky Highlands and *(ii)* the Western Alluvial Plains (Fig. 2). The Eastern Rocky Highlands that show an altitude variation from 300 to 1100m, are the extensions of the major mountains of western India – the Aravalli, Satpura and the Sahyadri. The hilly areas of the north form the SW extremity of the Aravalli mountains.

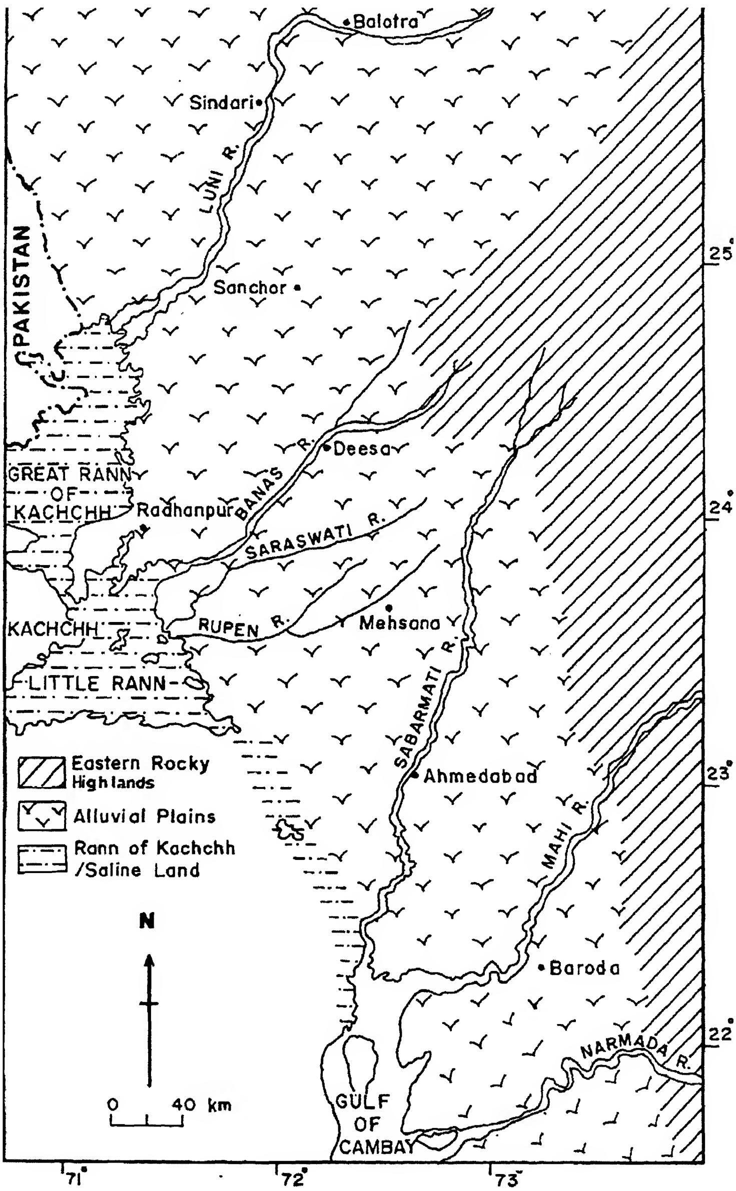


Fig.2 Map showing the major geomorphic divisions

The Aravalli hills within the Gujarat state do not show any well-defined directions, but regionally they conform to the NE-SW trends. The rocks belong to the Delhi and Aravalli Supergroups with associated intrusives. A majority of the hills fall within an altitude range of 300 to 600m. The central part of the hilly terrain, lying between the Mahi and Narmada rivers, referred to as Vindhyan range provides an example of topography typical of Archean metamorphics and granitic rocks; no specific trend is observed. The altitude ranges between 150 and 500m, the average heights being ~350m. The rocky area to the south of Narmada is included in Sahyadri, and the area especially beyond Tapi river is characterized by E-W trending hill ranges of basalt : from north to south shows a progressive increase in altitude with a step-like topography. Elevationwise, a major part of the trappean highland shows an altitude variation from 150 to 300m.

The *Western Alluvial Plains* are made up of a thick pile of unconsolidated sediments deposited by a combination of fluvial and aeolian agencies during the Quaternary period. Forming the western half of the Mainland Gujarat, the altitude variation of the plains ranges from 25 to 150m with a gradual seaward slope. These plains of North and Central Gujarat in their deepest parts are very thick and could be as deep as 500m or even more at places. Across these plains flow the major rivers of Gujarat.

Climate

Gujarat, being located on the Tropic of Cancer, falls in the sub-tropical climatic zone and a large part of the state lies between 35 °C and 45 °C isotherms. The rainfall in the state is moderate as it forms a transitional zone between the heavy monsoon area of Konkan (Maharashtra) in the south and the arid areas of Rajasthan in the north.

On the basis of climate, Gujarat is divisible into following five regions: (1) Sub-humid South Gujarat (Surat, Valsad, Dangs), (2) Moderately humid Central Gujarat (Bharuch, Vadodara, Panchmahals, Sabarkantha and parts of Ahmedabad), (3) Humid and sultry South-facing coastal region of Saurashtra, (4) Semi-arid North Gujarat (parts of Sabarkantha and Ahmedabad and Gandhinagar), and (5) Arid North Gujarat (Mehsana and Banaskantha).

March onwards the temperature starts rising till it reaches the maximum, as high as 45 °C, in some parts of the state. January is the coldest month when the maximum temperature never exceeds 30 °C and the minimum temperature remains around 8 °C to 10 °C. The region receives much of its rainfall from the southwest monsoon during the period between June and September, its maximum intensity being in the months of July and August. The rainfall gradually decreases northward; in the southernmost part (Valsad and Dangs) it is around 2000mm, while in the extreme north it is as low as 300mm (Fig. 3). The relative humidity in all parts of the state is low, though in the coastal areas it is moderately high.

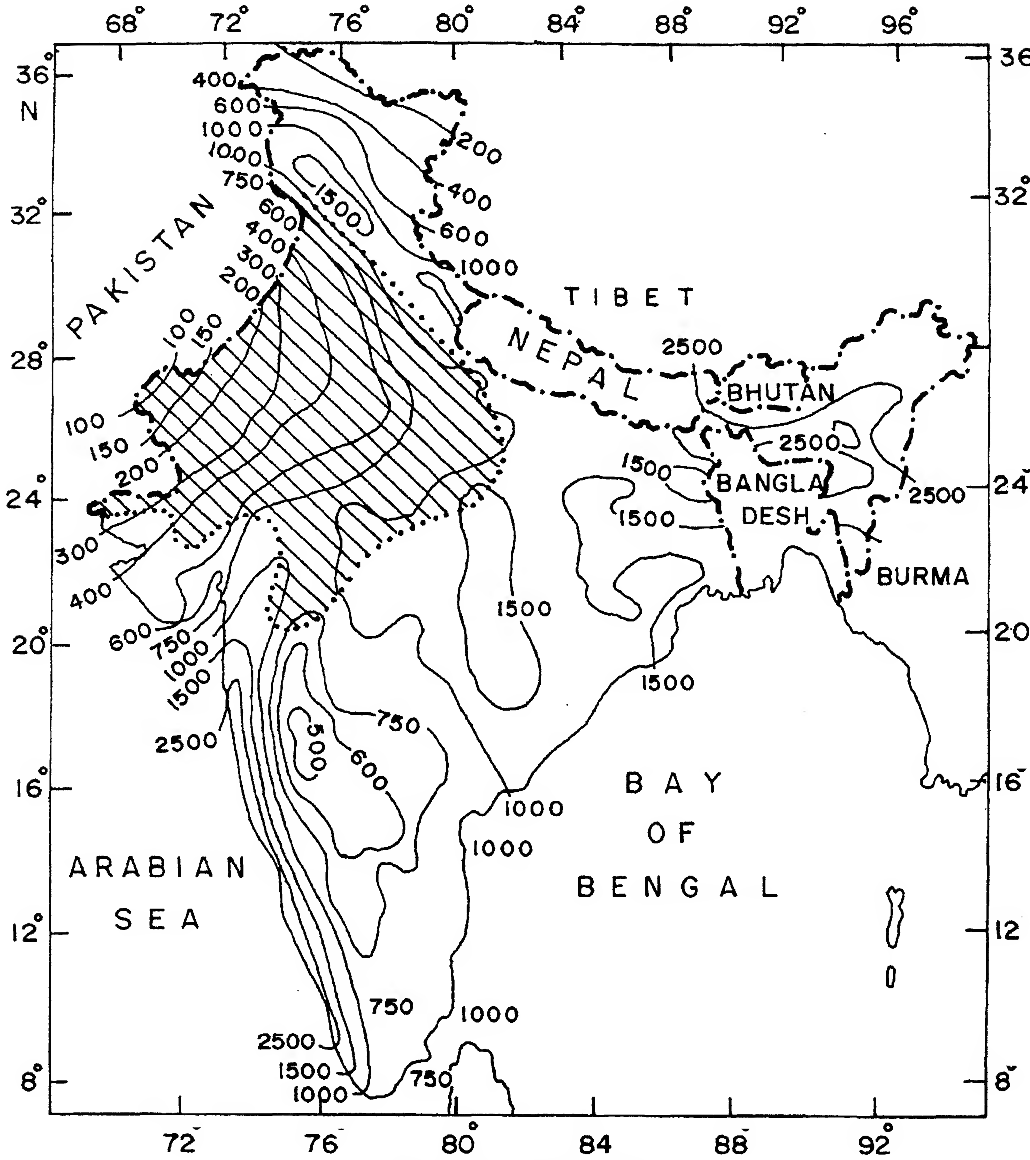


Fig.3 Isohyet map of India[1]

The winds are generally light to moderate, increasing in intensity during the late summer and monsoon season. Coastal areas experience stronger winds. The winds blow from W or SW during the monsoon months and NE to NW from October to April.

The study area falls within the arid and semi-arid zones and is marked by the variability of annual rainfall and high annual temperature extremes. The climate in general is dry except for the monsoon season. The winter season starts from December and extends upto February. Summer approaches from March and peaks

in May and June. The monsoon rain starts from the middle of June and continues upto September. The rainfall pattern (continuity, intensity and frequency) is of great importance for the Gujarat plains, particularly as they are situated on the margins of the Thar desert. During the summer months, the mean daily maximum temperature is around 40 °C and mean daily minimum temperature around 25 °C, although temperatures touching peaks of 44-45 °C are not uncommon. Clear skies, low humidity and light northeasterly, northerly and northwesterly winds characterize the winter season. During the coldest month of January the normal minimum temperature varies from 7 °C to 18 °C (mean around 14 °C); occasionally the mercury dips below to 3-4 °C.

Drainage

Drainage of the Mainland Gujarat has been controlled by the factors of physiography, geology (tectonics) and climate (past as well as present). It shows two distinct sets of rivers (Fig. 4). Rivers occurring in the northwestern part (Rupen, Saraswati and Banas) arise from Aravalli hills and flow into the Ranns of Kachchh. These rivers have courses of about 150 km lengths at the maximum and are more or less seasonal carrying water only during the monsoons. Interestingly, these rivers though shallow, have wide sandy channels in their lower reaches.

The rivers draining the central and southern parts fall into the Gulf of Khambhat and the Arabian Sea. Major rivers are Sabarmati, Mahi, Narmada and Tapi. The Sabarmati river originates in the southwestern spurs of the Aravalli hills and traverses a distance of 416 km through the districts of Sabarkantha, Ahmedabad and Kheda before meeting the Gulf of Khambhat. Interestingly, the river has, in its upper reaches cliffy banks rising upto 50m. In its lower reaches, the river is seen to have frequently changed its course. The plains of Central Gujarat lying between Sabarmati and Mahi are drained by a number of tributaries of Sabarmati, viz., Khari, Shedhi, Mejan, Andheri, Meshwo and Vatrak. Of these, Meshwo and Vatrak are the major ones. Meshwo originates in Dungarpur district of Rajasthan and meets the Vatrak river. The Vatrak also rises from the Dungarpur hills and meets Sabarmati at Vautha. The river Shedhi which forms the chief drainage of the alluvial plains between Sabarmati and Mahi originates from the eastern hills of Panchmahals district and meets Vatrak at Kheda.

The river Mahi, the third largest river of Gujarat after Narmada and Tapi, rise from about 556m above sea-level in the Malwa region around Sardarpur in Madhya Pradesh. It flows for about 180km in Gujarat before emptying into the Gulf of Khambhat. The lower course of the river for about 70km is characterized by heavily gullied cliffy sand-banks and ravines. Further south, the river Dhadhar rising from the Shivrajpur hills also flows into the Gulf of Khambhat. This river is met by a major tributary Vishvamitri, 25km SW of Vadodara.

The river Narmada originating in the hills of Amarkantak in Madhya Pradesh, 1150m above the sea-level, cuts through the hill range of Satpura and Vindhya

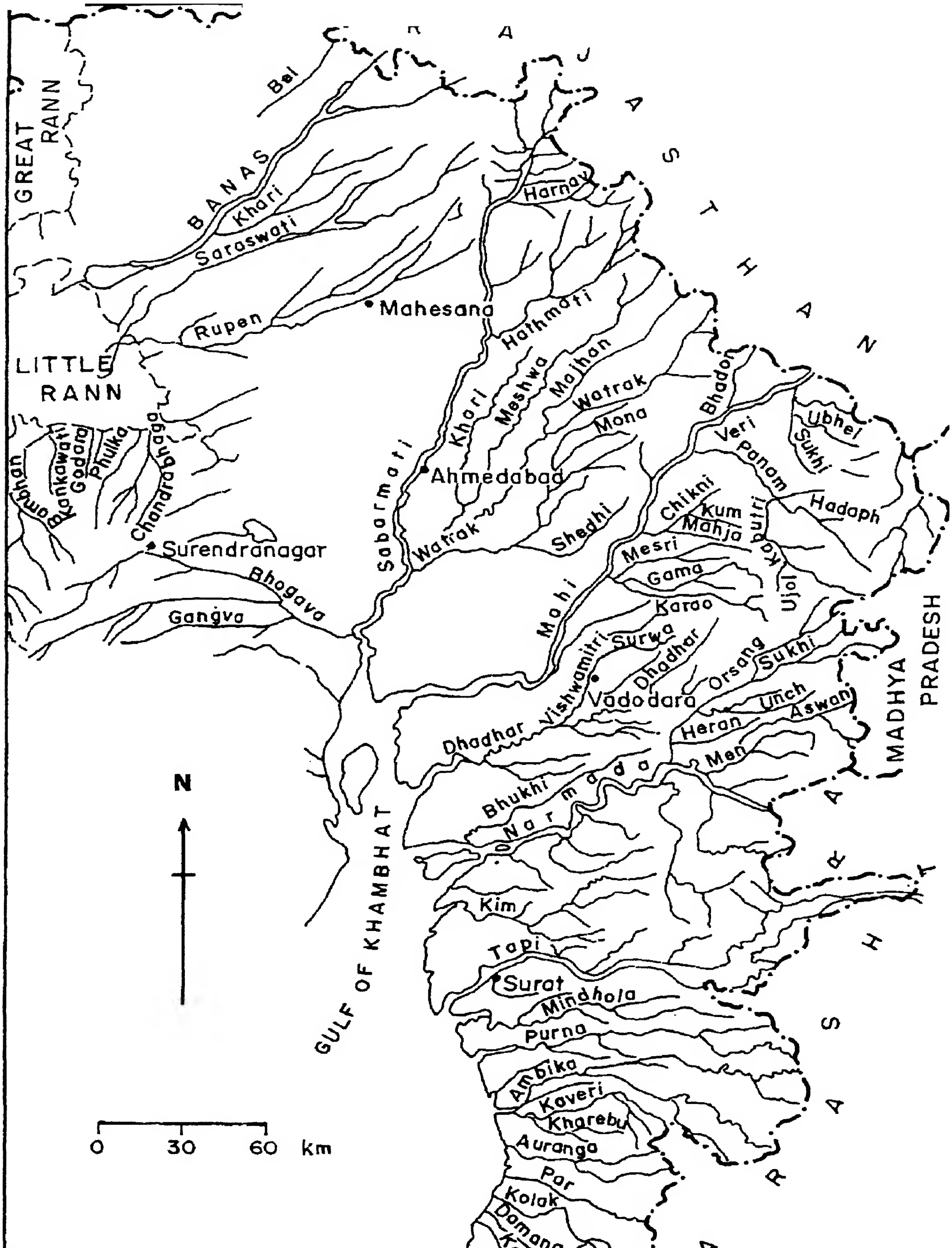


Fig.4 The present drainage system of the alluvial plains

before entering Gujarat, and as is well known, this river flows along a major geofracture zone. Within the Gujarat State it has a 150km long course and finally falls into the Gulf of Khambhat near Bharuch. The Orsang river is a major tributary of Narmada, meets it on its right bank at Chandod; on the left bank, the river Karjan flows into Narmada at Rundh. Lower down its course between Shuklatirth and Bharuch, three more smaller tributaries namely viz., Kaveri, Amravati and Bhukhi, join the main river. For almost 100km, the Narmada flows across the most fertile plains of Gujarat. Other rivers to the south of Narmada (Damanganga, Kolak, Par, Purna, Auranga, Ambica and Mindhola) of South Gujarat are comparatively smaller and rise within the boundaries of the state from the eastern trappean highlands.

Tapi river, after flowing through Madhya Pradesh and Maharashtra, enters the trappean highlands of Gujarat and runs for about 100km before meeting the sea, 10km west of Surat. As compared to Narmada, Tapi is a smaller river but the area drained by it in Gujarat is quite large. The lower Tapi valley is very fertile and covered with black cotton soil. The Kim river rises in the Rajpipla hills and flows into the Gulf of Khambhat.

Soils

The surface soils of the alluvial plains of Gujarat (Fig. 5) show much diversity and can broadly be classified into following five orders: (1) Entisols, (2) Inceptisols, (3) Vertisols, (4) Alfisols and (5) Aridisols.

Entisols have developed over traps, granites, gneisses, quartzites and alluvium; light grey, greyish brown and reddish brown in colour; well distributed in Saurashtra, North Gujarat, and in parts of Kachchh and Mainland Gujarat. Inceptisols have derived from basaltic, granitic, gneissic and alluvial parents; dark grey to light grey, reddish brown, yellowish red and dark reddish brown in colour; found in parts of Mainland and Saurashtra. Vertisols occur in the districts of Bharuch, Surat and Valsad in South Gujarat, Mehsana and eastern parts of Ahmedabad districts, northern parts of Kheda and Baroda districts in Central Gujarat and Bhal and Ghed tracts of Saurashtra. These are generally deep black in colour; however at places they show dark brown to very dark greyish brown colours. Vertisols are locally known as 'Regurs' or Black cotton soil. Morphologically, they are mainly confined to uplands, piedmont plains, flood-plains and intervening valleys and occur mainly under semi-arid to sub-humid and humid climates with annual precipitation's more than 500 to 2000mm and mean annual temperature of 26 °C to 27 °C. The total soil depth varies from 50cm to as high as a few meters. These are mainly clayey soils with montmorillonitic mineralogy having high shrink-swell potential. Structurally, they are sub-angular, blocky with polygonal cracks on the surface. These soils are neutral to alkaline in reaction and are classified as Chromusterts and Usterts. Alfisols are the products of the sandstone and at places

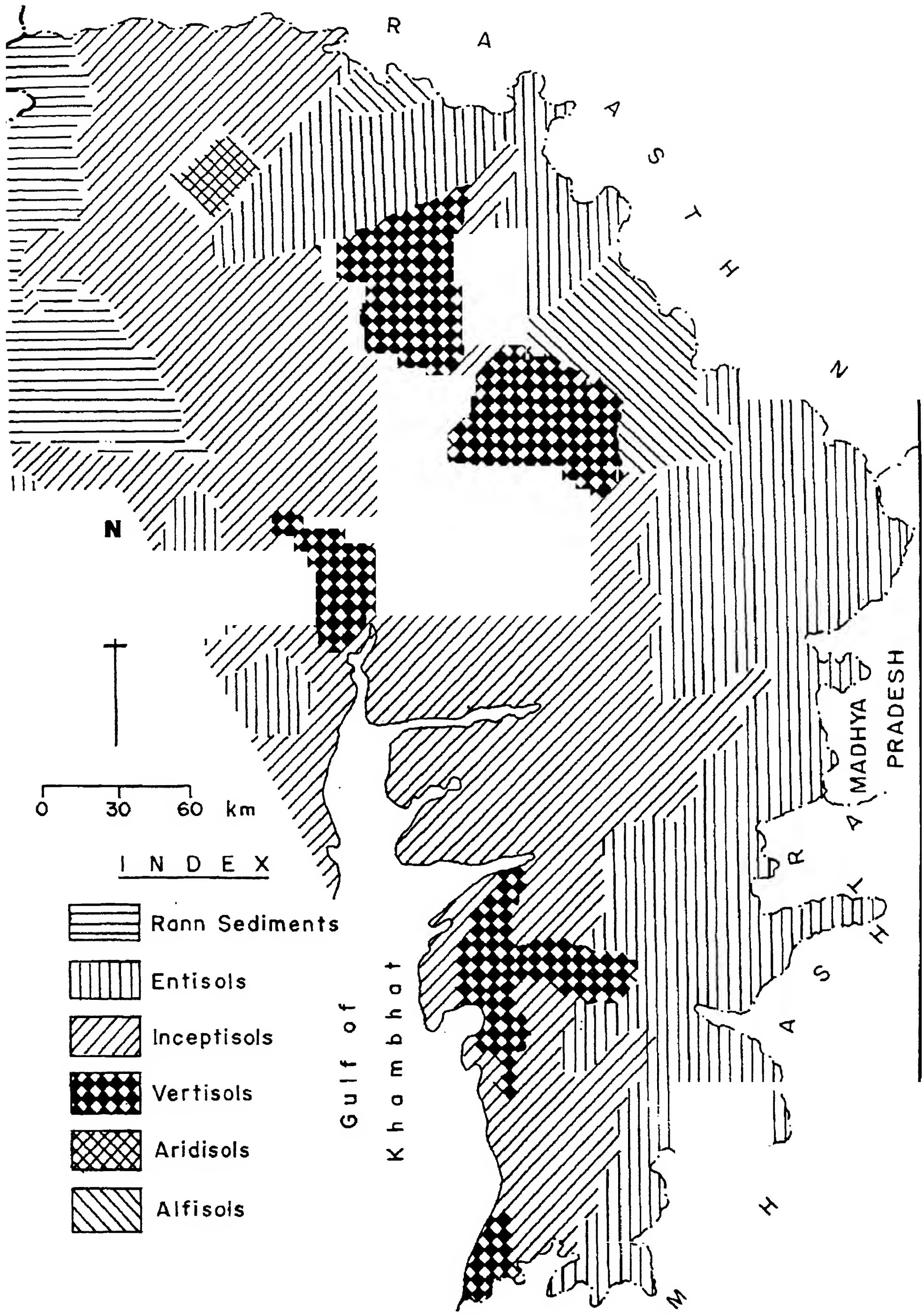


Fig.5 The major surface soil types of the alluvial plains

over alluvial deposits; mostly reddish to reddish-brown in colour found in northern part of Mainland and some parts of Saurashtra.

Geology

The geology of Gujarat comprises a Precambrian basement over which younger rocks commencing with Jurassic, continuing through Cretaceous, Tertiary and Quaternary have given rise to varying sequences in different parts. Thus the rocks of Gujarat belong to formations ranging in age from the oldest Precambrian to Recent. Stratigraphically, the record is incomplete as the rocks of Paleozoic Era are totally absent (Fig 6). The sedimentary and volcanic rocks rest over the southwesterly extended Proterozoic rocks of Rajasthan and the post Triassic. The major geological events of Gujarat thus are confined to Mesozoic and Cenozoic Eras. The geological evolution of Gujarat initiated in the Triassic with the break up of Gondwanaland and the subsequent geological history is related to the northward drift of the Indian subcontinent.

The Mesozoic and Cenozoic tectonism related to the break up of the Western Continental Margin and the subsequent drift of the Indian Subcontinent has mainly controlled the geological evolution of Gujarat. The depositional history and Deccan volcanism are part of this major tectonic phenomenon[2]. The structural set-up is controlled by a number of Precambrian basement tectonic lineaments, trending *(i)* NE-SW and *(ii)* E-W to ENE-WSW and *(iii)* NW-SE. Narmada geofracture forms an important tectonic feature of Gujarat. Reactivated movements along these Precambrian trends due to break up of the Gondwanaland (and the subsequent NNE drift of the Indian landmass) gave rise to three important basins of Kachchh, Cambay and Narmada, which in turn, controlled the geological evolution of the three distinct parts of Gujarat, viz. Kachchh, Saurashtra and Mainland[2]. The geology of Mainland Gujarat is represented by Precambrian crystallines, sedimentary rocks of Cretaceous, Tertiary and Quaternary periods and the Deccan trap (Fig. 6, Table I).

The geological evolution of its northern and eastern parts has been controlled by the Precambrian orogenies – Aravalli and Delhi cycles, and the older crystalline rocks ideally show folds, faults and magmatism related to the two orogenies. The major portion of the Mainland however, exhibits imprints of the Mesozoic and Cenozoic events, and the various rock formations reflect the uplifts and subsidences along the two major lineaments, Narmada and Cambay rift systems. The Cretaceous and Tertiary sedimentary basins are fault controlled and manifest the tectonism related to these two major fracture trends. Whereas the Cretaceous sedimentation and existing distribution and outcrop pattern clearly show an E-W trending fault control, the Tertiary rocks are deposited in the tectonic basins bound both by N-S and E-W faults.

A major part of the Mainland falls within the Cambay and the Narmada grabens and the eastern and the northeastern Precambrian rocks mark a tectonic

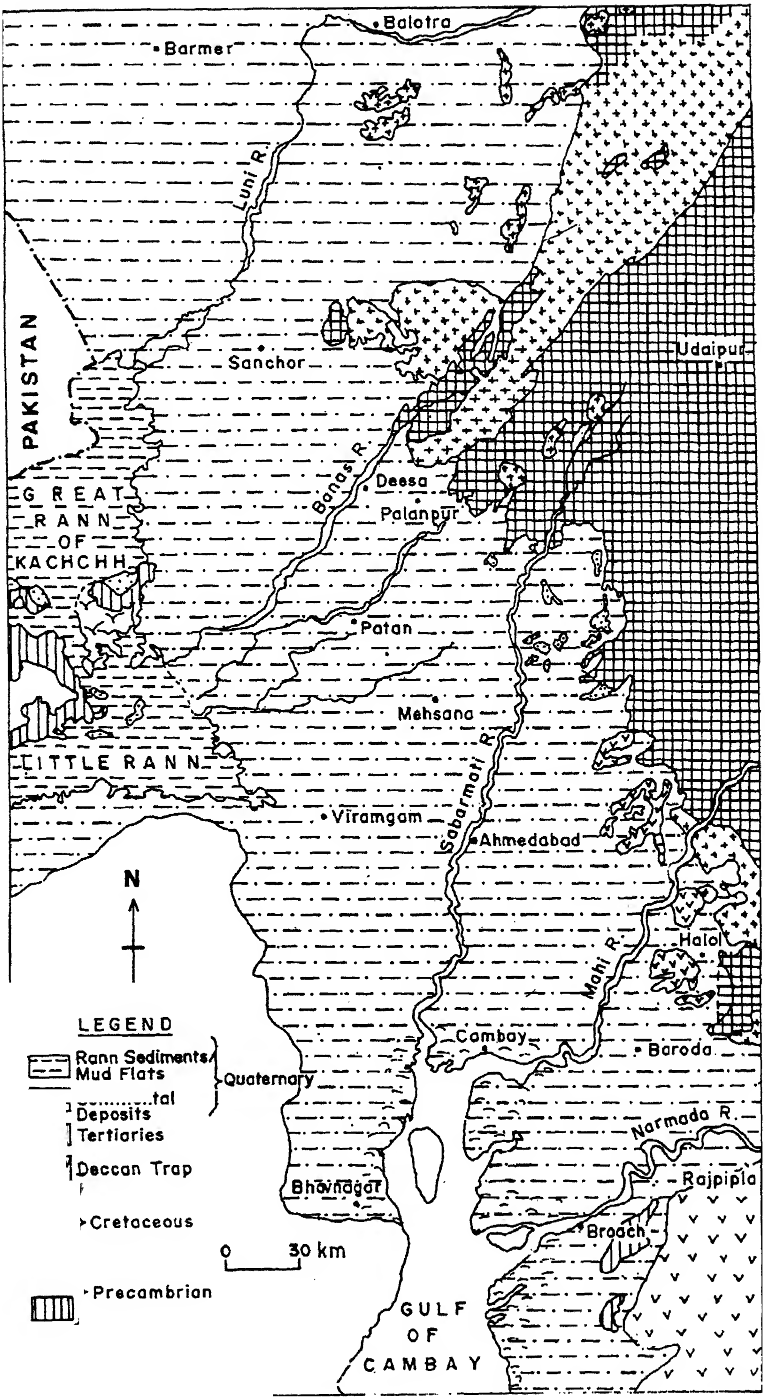


Fig.6 A generalised geological map of Mainland Gujarat and SW Rajasthan based on the work of GSI

Table I Stratigraphy of Mainland Gujarat

STRATIGRAPHY				MAINLAND GUJARAT	
ERA	PERIOD	AGE		GROUP / FORMATION	LITHOLOGY
CENOZOIC	QUATERNARY	HOLOCENE		GUJARAT ALLUVIUM / NARMADA FM	SAND, SILT, CLAYS WITH GRAVEL BEDS
		PLEISTOCENE	U		
			L	JAMBUSAR FM (NOT EXPOSED)	COARSE, SAND, CLAYS, KANKARS
	TERTIARY	PLIOCENE	U	BROACH FM (NOT EXPOSED)	CLAYSTONE, SANDSTONE
			L	JHAGADIA FM	CONGLOMERATE SANDSTONE
		MIOCENE	U	KAND FM	CONGLOMERATE, FOSSIL, LIME-STONE, CALC SANDSTONE
			L	BABAGURU FM	CONGLOMERATE SANDSTONE
		OLIGOCENE			
		EOCENE	U	DINOD FM	FOSSIL, LIMESTONE, MARL
			L	VAGADKHOL FM	CONGLOMERATE, GRIT SANDSTONE, CLAY, SILTSTONE
		PALAEOCENE		LATERITE / DECCAN TRAP	BAUXITE BENTONITE / THOLEIITE AND ALKALI BASALT
MESOZOIC	CRETACEOUS		U	DECCAN TRAP / LAMENTA	FLOWS & INTRUSIVES / LIMESTONE
			L	BAGH BEDS / NIMAR SANDSTONE	LIMESTONE, MARL, SANDSTONE
	JURASSIC		U M L		
PROTEROZOIC	POST-DELHI MAGMATISM			MALANI VOLCANICS	ANDESITE ALBITISED BASALT
				ERINPURA GRANITE	POTASH GRANITE, MICRO-GRANITE, GRANITE PORPHYRY
				GODHRA GRANITE	GRANITE, GRANITE GNEISS
				POST-DELHI-PRE-ERINPURA GRANITE PHASE	META-GABBRO META-DOLERITE, EPIDIORITE
	DELHI SUPERGROUP			SIROHI GROUP	PHYLLITE, MICA-SCHIST, CALC SCHIST
				AMBAJI GRANITE	GRANITE GRANODIORITTE GRANITE GNEISS
				KUMBHALGARH GROUP	CALC SCHIST, CALC GNEISS, MICA SCHIST, MARBLE
				GOGUNDA GROUP	QUARTZITE SLATE, CALC SCHIST
	ARAVALLI SUPERGROUP			CHAMPANER GROUP	SLATE, PHYLLITE, QUARTZITE WITH MANGANESE
				LUNAVADA GROUP	PHYLLITE, BIOTITE SCHIST, QUARTZITE, DOLOMITE
				RAKHABDEV ULTRAMAFIC SUITE	TALC-SERPENTINE SCHIST WITH TREMOLITE-ACTINOLITE
				JHAROL GROUP	PHYLLITE, CHLORITE SCHIST, QUARTZITE CRYST, LST
	AGE UNCERTAIN			**BASEMENT**	**GRANITE AND GNEISS**

boundary. The Eastern Cambay Basin Bounding fault extends almost N-S across the middle of the Mainland broadly delineating the Quaternary deposits from older rocks. The structure is reflected in the topography which typically show progressive stepping down from south to north along E-W faults and from east to west along N-S faults. The coastline is again a fault-line feature.

Previous Work

The alluvial plains of Gujarat and Southwest Rajasthan have attracted attention of geologists, pedologists and archaeologists for almost a century. Blanford[3] was the first person to describe the alluvial deposits of the Narmada and Tapi river valleys.

Foote[4] surveyed the area falling within the former Gaekwad's state of Baroda and described the various alluvial and sub-aerial formations of some of the major rivers. His is the first ever detailed description of the alluvial horizons exposed in the cliff sections of the Sabarmati and Mahi rivers. Emphasizing on the Sabarmati cliff sections he opined that the rivers Sabarmati and Mahi at present are more destructive than constructive and the extent of deposition is negligible. Sankalia[5] studied Sabarmati from the archaeological point of view and fixed a Lower Paleolithic age limit for the base of the exposed succession on the basis of lower Paleolithic tools recovered from the basal gravels.

Zeuner[6,7] was the first worker to provide details of the Pleistocene chronology of Gujarat. He investigated the deposits exposed in the valleys of Sabarmati, Mahi and Narmada and paid greater attention to the deposits of Sabarmati valley. The Orsang river, a tributary of Narmada was also studied in detail, where stratigraphic and climatic sequences identical to those of Narmada were recognized. Zeuner[6] envisaged climatic changes during the deposition of the entire continental succession comprising repeated oscillations between dry and wet climatic conditions. Wainwright[8] described the Pleistocene deposits of the Lower Narmada valley and gave details of the cliff sections and emphasized the role of sea-level in the deposition of the sediments.

The work of Allchin *et al.*[9], which deals with the entire Thar desert of Rajasthan and the arid plains of North Gujarat provides an excellent perspective of the Quaternary aeolian deposits of Western India in terms of pre-history. They provided a good insight into the diversity of environment during which the early man lived in this part of the sub-continent. Ghose *et al.*[10], suggested that none of the present day rivers in south Rajasthan played any significant role in the formation of the alluvial plains of the region. These authors visualised existence and role of a Himalayan river in the alluviation process in the Luni basin. Their observations in Lower Luni basin and Sabarmati rivers furnish valuable information relevant to the present study. Wasson *et al.*[11], who mapped the Thar dune-fields found that the dunes overlap sandy alluvial deposits and the entire succession underlying

the dunes in North Gujarat is fluviatile. Rajaguru[12] and Misra and Rajaguru[13] studied in detail the problem of late Pleistocene aridity.

Whereas most previous workers mentioned above invoked the factor of climate-late Pleistocene humidity followed by pre-Holocene (Terminal Pleistocene) aridity to explain the phenomena of drainage disruption and evolution of the present day landscape, Ahmad[14] added a new dimension to this problem by invoking the dominant role played by Holocene tectonism. He contended that the rivers changed their courses in response to epeirogenic activity and the deposition of the alluvial fans, their shapes and rates of deposition depended dominantly upon epeirogeny. Kar[15-17] has critically evaluated the phenomena of drainage disruption, climate-related fluvial processes and role of neotectonism in the Thar desert and highlighted the tectonic control in the evolution of ancient and modern drainage systems. Subsequent studies mostly by geologists and physicists have aimed at precise dating of the various formations and also to understand the depositional processes and environments. Studies by Singhvi *et al.*[18], mainly pertain to the application of Thermoluminescence methods in dating the various aeolian phases and to understand the chronology of paleoclimatic changes.

The continental Quaternary deposits of Gujarat in recent years have received significant attention[19-33]. Studies carried out by Chamyal and associates[19-30] mainly pertain to the depositional succession, gross-lithology and paleoclimatic evidence as revealed in the various river sections of the Narmada, Mahi and Sabarmati. Sareen *et al.* [31-32] have attempted to provide a tentative chronological succession for the Sabarmati deposits using Thermoluminescence and the role of Quaternary tectonism in shaping the present landscape. Sridhar *et al.*[23,29], have provided more details on North Gujarat. These authors have invoked non-marine (mostly fluvial) sedimentation in a huge graben bounded by Cambay Basin related faults. The alluvium is as thick as 300m even in the areas devoid of any present day drainage, obviously the entire alluvial succession was a product of an ancient-fluvial system which has since been partly destroyed. A combination of neotectonic activity in the Cambay Basin, glacio-eustatic sea-level changes and paleoclimatic fluctuations appear to have played a major role in controlling the depositional history of the fluvial sequence and the disruption of the super-fluvial drainage system.

Geomorphology

The vast alluvial plains, look uninteresting and monotonous but a careful and in-depth appraisal of the terrain with the help of topographical sheets, satellite images and field studies reveal very interesting details. They show an array of geomorphic features which are the reflections of the various tectonic, erosional and depositional processes of the late Quaternary.

The Gujarat plains are situated in a geological setting flanked by Precambrian rocks in the east and by the Mesozoic rocks, comprising both sedimentaries as

well as volcanics, in the west and south. The overall topography (Fig. 7) is a product of a combination of numerous tectonic lineaments (faults, joints etc.) which mark the limits of the rocky highlands and also control the behaviour of most of the rivers.

Alluvial Plains

Commonly referred to as Gujarat Alluvial Plains, these form the median part of Mainland Gujarat extending from Nàrmada river in the south to the Luni river in the north. A generalised geomorphic map based on satellite images, topographic maps and field surveys, show the landscape diversity of these plains (Fig. 8). Showing a gradual slope from ENE to WSW, the plains range in altitude from 150m to almost sea level (Fig. 7). They are broadest between Mahi and Banas rivers. From the gradient point of view these plains could be divided into four segments, the terrain between the rivers *Narmada* and *Mahi* has an undulating hummocky surface with a regional slope towards SW. It is flanked to the east by the Panchmahal uplands. Most of the tributaries of the Narmada (Orsang, Heran, Men and Karjan) and the Mahi (Anas, Panam, Karad and Mini) originate in these uplands. The Dhadhar and the Vishwamitri constitute the other rivers of this segment. These follow generally either a NNE-SSW or E-W course. Pavagadh (Δ857m), Phenai-Mata (Δ481m) and Ambadungar (Δ611m) stand out as the discrete rocky elevations within this segment. The area along the river Mahi is characterised by a striking ravine topography.

The slope of the plains between *Mahi* and *Sabarmati* is SSW-ward and shows a drop of almost 50m in a distance of 40km. The various smaller rivers that drain this segment follow a south-southwesterly course; in lower reaches however, all the rivers take a westerly trend before finally meeting the Sabarmati. This phenomena perhaps is due to a westerly slope. The segment between Sabarmati and Banas, though showing an overall slope to the SW tends to show increasing gradient from E to W. This factor of slope is well illustrated in the various rivers which, irrespective of their place of origin flow SW and W and either meet Banas river or the Little Rann. The gradient in the upper part of the segment is relatively high but in the lower reaches the slope tends to decrease considerably almost showing negligible values—a drop of only 100m in a distance of 100km. The plains lying between the rivers Banas and Luni are also characterised by a very gentle slope due west. Except for the eastern part of the segment where the slopes are slightly higher, its major portion shows a very low gradient. A characteristic feature of this segment is the near total absence of any southwest flowing rivers.

The overall landscape tends to be increasingly dunal from SE to NW. The surface topography between Mahi and Sabarmati is typically flat and featureless but on crossing Sabarmati, proceeding northwards, the plains become increasingly undulating and are endowed with numerous dunal mounds. The landscape is

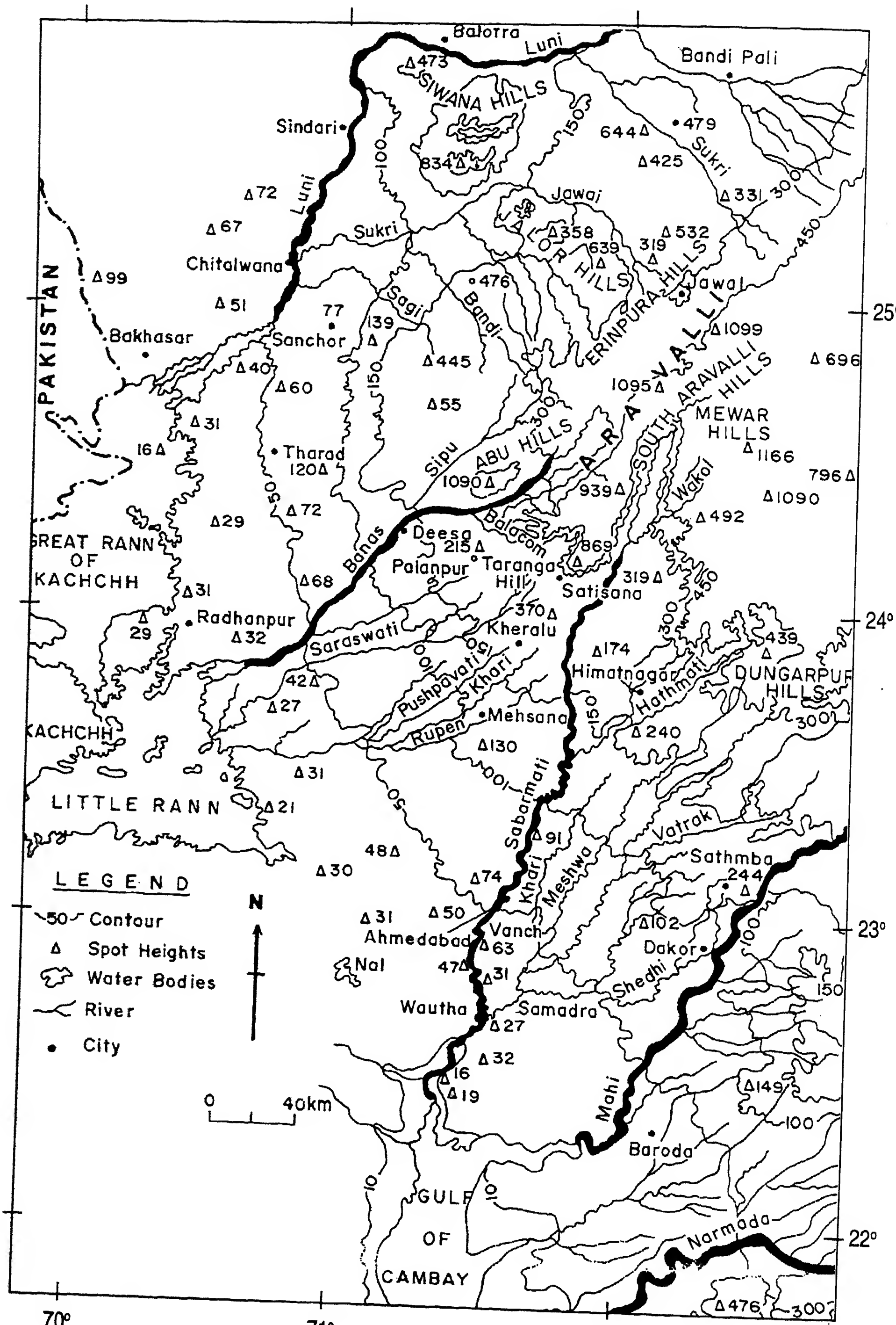


Fig.7 Physiographic map of the alluvial plains

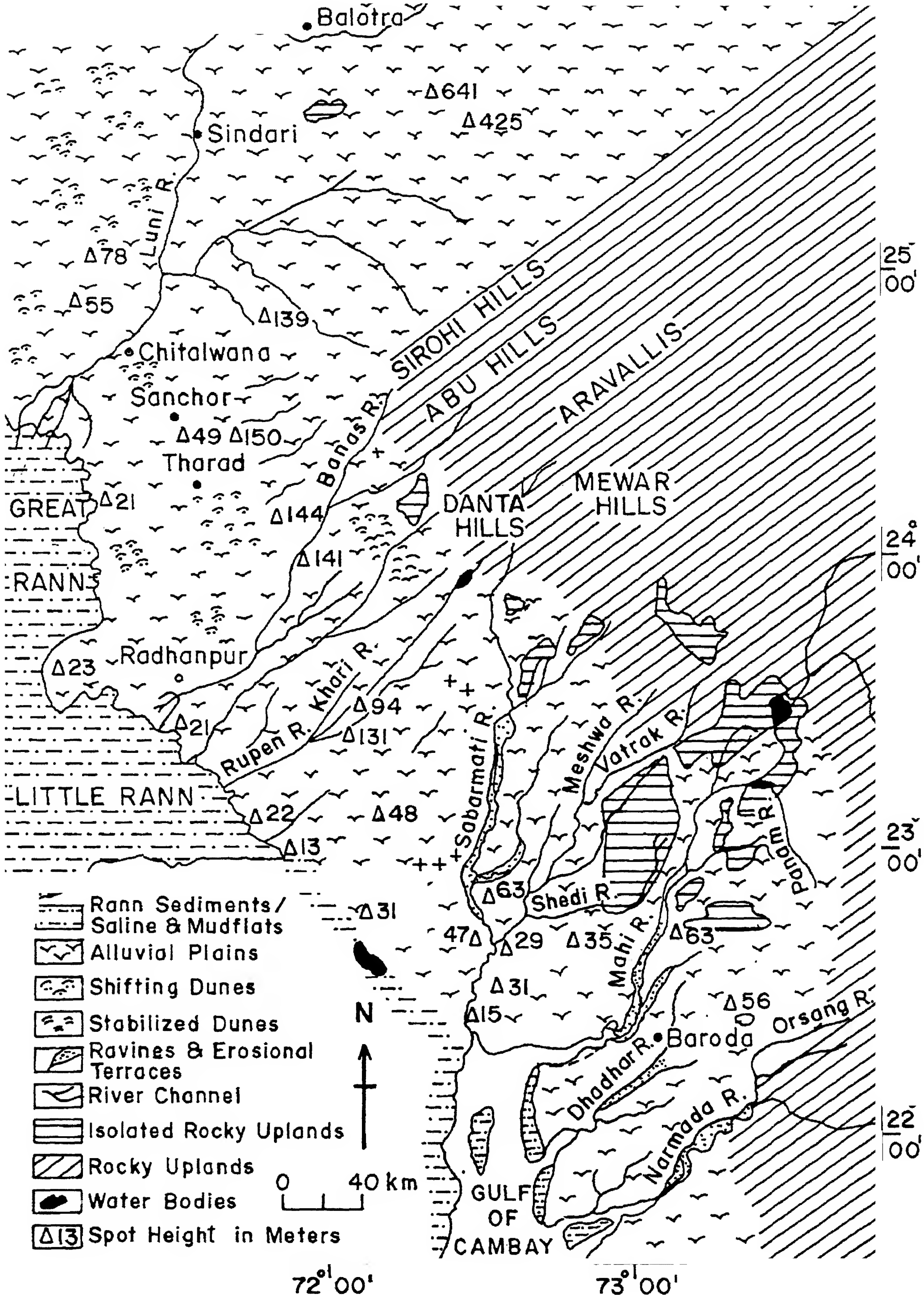


Fig.8 A generalised geomorphological map of the alluvial plains

characterized by a very well defined uneven topography and numerous dunal hills rise several meters above the ground level (Diodhar Δ73m, Ogadpura Δ109m, Tharad Δ59m, Langhnaj Δ79m). A characteristic feature of the area south and west of Luni within Gujarat is replete with stabilised dunes dissected by ill defined stream courses. These dunes are stabilised and indicate a period of aridity followed by a phase of increased humidity.

North of Banas right upto Luni and beyond, dunes and sand ridges of unconsolidated fine sand, are very common. In fact these dunes are the indicators of the northern limit of the Gujarat plains, beyond which they go below the sands of the Thar desert. The nature of topography in the extreme north marking the boundary of Gujarat is also of some interest. Whereas north of the boundary, the terrain has a better development of consolidated and unconsolidated dunes, southward in Gujarat except for a few sporadic stabilised dunes the unconsolidated sand accumulations are much less. Altitudewise, the Gujarat portion is somewhat higher by about 10m; the rise is abrupt and more or less coincides with the State border.

Tectonic Framework

Interaction between sedimentation and tectonics is now an established fact, though the phenomenon is not yet fully understood. However, the effectiveness of tectonic factor is implicit on two counts :

(i) A basin providing a site for the accumulation of sediments, and

(ii) An uplifted area from where sediments would be derived.

Tectonism has played an important role in the evolution of Gujarat plains at all stages[24-27] The control exercised by the various structural lineaments was quite effective and dominant all-throughout the Tertiary and Quaternary and the sediment accumulated in structural basins that developed at the close of Cretaceous. All along, especially during Quaternary, the factors of glacio-eustasy and palaeoclimate combined to sustain and control the deposition. According to Biswas[2], the tectonic activity was initiated as early as the close of Triassic when the Gondwanaland started breaking up, and sometime in the late Cretaceous the western continental margin developed a major rift, as a result of which a regional structural fault-bound depression extending from Rajasthan southward to Narmada and beyond (Fig. 9), came into existence. Referred to as Cambay Basin in Gujarat, it consists of two large fault bound depressed blocks N-S Cambay and E-W Narmada grabens (Fig. 10).

Initially, marine deposition took place in the basin during major part of the Tertiary, but in its later evolutionary phase, during the Quaternary, the filling up was mainly by the fluvial and aeolian sediments, consequent upon the withdrawal of the Tertiary sea. Whereas, the main bulk is a Tertiary sequence confined to the limits of the Cambay Basin, the overlying Quaternary deposits are seen to

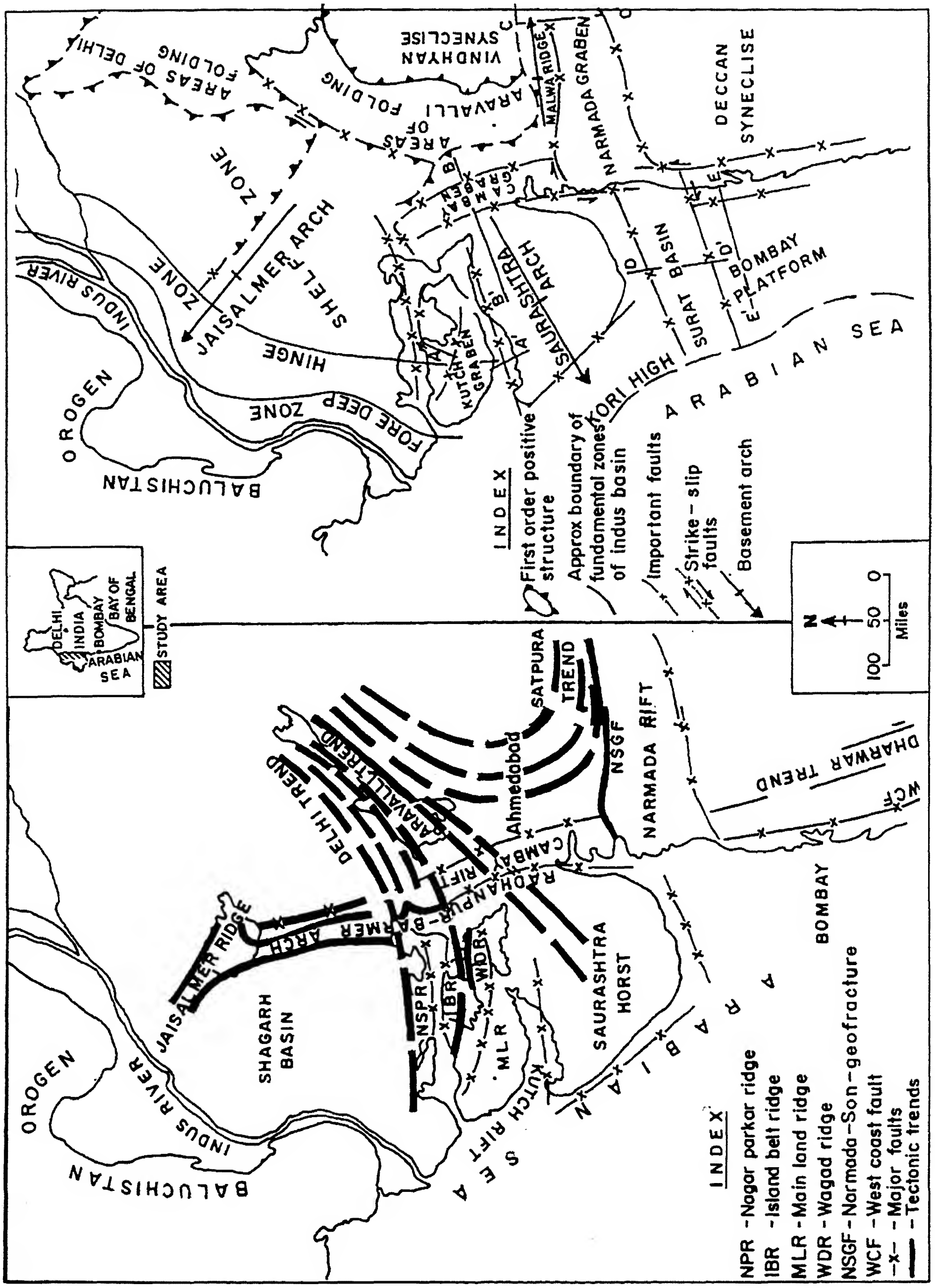


Fig.9 Tectonic framework of Western India[2]

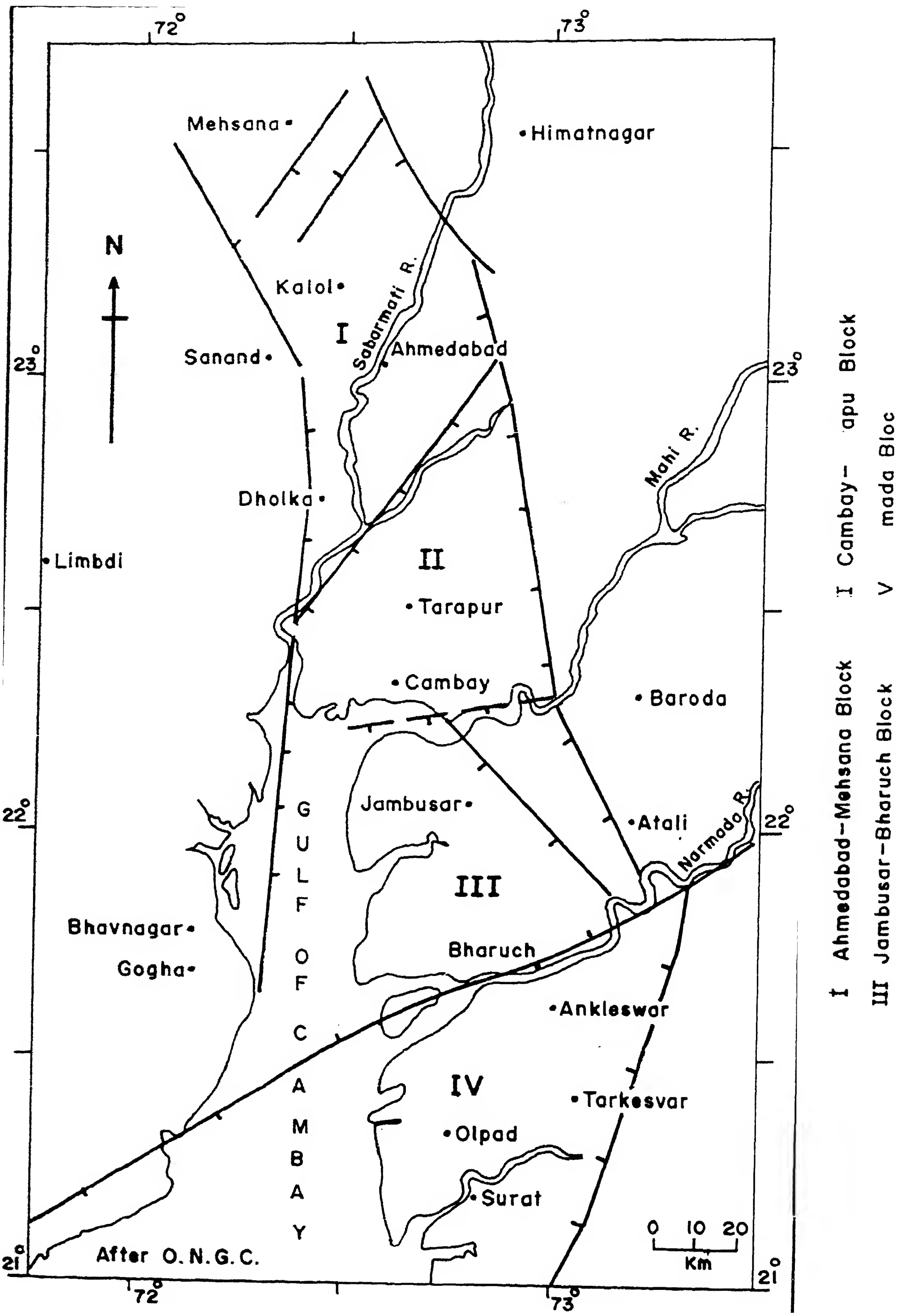


Fig.10 Tectonic map of Cambay Basin[37]

have overfilled the main basin, spilled over the Tertiary basin crossing the Eastern Margin Cambay Basin Fault (EMCBF) and deposited even beyond, resting directly over the basement. A subsidence of the basin concomitant with the accumulation of sediments facilitated deposition of ènormous quantity of sediments. This progressive deepening coincided with the uplift of the Saurashtra horst in the west, rejuvenation of the Aravalli in the NE and the uplift of the area to the south of Narmada (during Quaternary)[14]. The vast thickness and lateral expanse of the Quaternary sediments thus took place in a partially filled basin of phenomenal dimension, mainly because of the reactivation of pre-Quaternary faults and development of new faults. A large part of the younger sediments is confined to eastern flank of the basin and is dominantly fluvio-marine, fluvial and aeolian.

Structural Control

The Cambay Basin extends broadly in a NNW-SSE direction in the onshore and offshore parts of Gujarat. Northward, it swings due SW-NE merging into the Rajasthan Basin. Data generated by the ONGC, mainly on the Tertiary sediments, adequately reveal the basement configuration and the control exercised by cross-faults in dividing the basin into several tectonic blocks or sub-basins. Each tectonic block behaved somewhat differently during the deposition, on account of differential uplifts along the various bounding and transecting faults. The basement typically comprised fault-bound uneven surfaces made up of horst and grabens (Fig. 11). Movements along faults parallel as well as oblique to the main basin, controlled the thickness of sediments, even the Quaternary deposits in the different parts of the Cambay Basin and its eastern margin show variable thicknesses.

The cross-section showing thickness data (Fig. 11, 12) brings out the role of tectonism prior to and during deposition of Tertiary as well as Quaternary sediments. The varying thicknesses, thus are obviously due to the fact that the

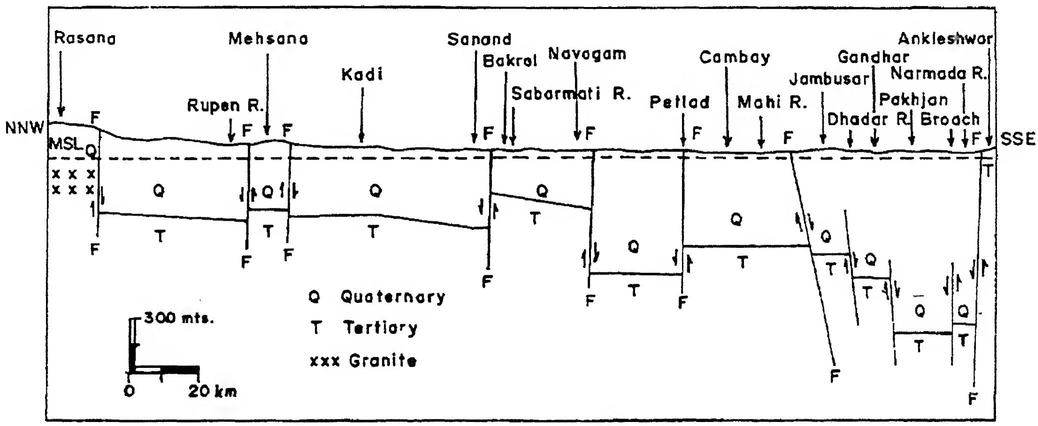
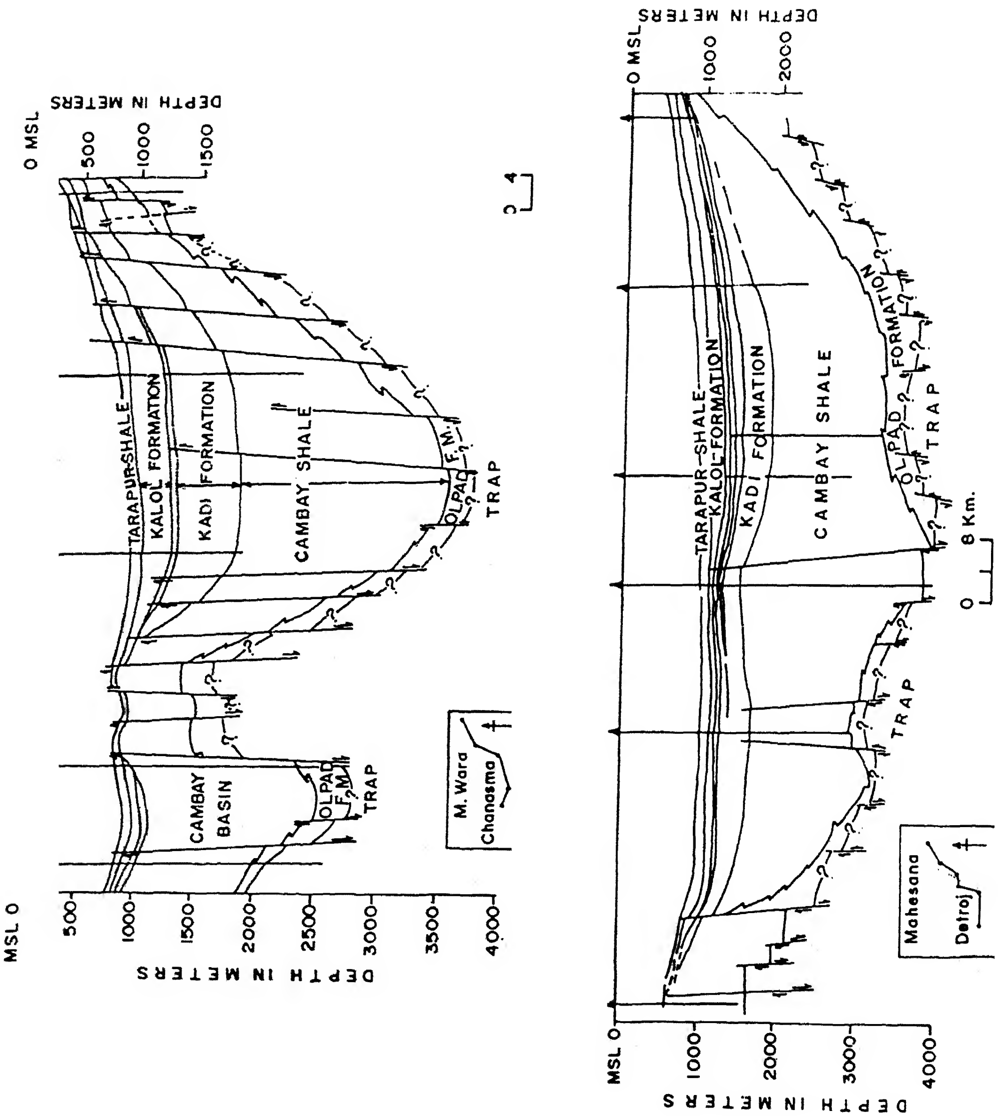


Fig.11 NNW-SSE section showing fault controlled basement[27]



DEPTH IN METERS
O MSL
500
1000
1500
2000
2500
3000
3500
4000
TARAPUR-SHALE
KALOL FORMATION
KADI FORMATION
CAMBAY SHALE
OLPAD F.M.
TRAP
CAMBAY BASIN
M. Wara
Chanasma
2000
C A M B A Y   S H A L E
OLPAD FORMATION
T R A P
0 8 Km.
Mahesana
Detroj

sediment accumulation took place in various fault bound depressions. The depositional sites continued to be unstable during the filling up of the basin, as the limiting faults, of the main basin as well as of the sub-basins, have affected the Quaternary sediments, their reactivation even after the deposition, has been well established. From the deep sounding seismic surveys (DSS) (Fig. 13) of Saurashtra and Mainland Gujarat, it has been established that the various major bounding faults, extend upto the Moho[34-36].

A perusal of the lineament map of the Gujarat and SW Rajasthan (Fig. 14) points to the close genetic relationship between the Cambay Basin tectonism and the Precambrian basement fracture pattern. The two Cambay Basin bounding faults (EMCBF and WMCBF) by and large, follow one or other structural trends; and so do the faults that dissect it into the sub-basins. The various post-depositional faults, responsible for the development of new drainage and the two Ranns of Kachchh, also conform to the basement fracture trends.

Tectonic History

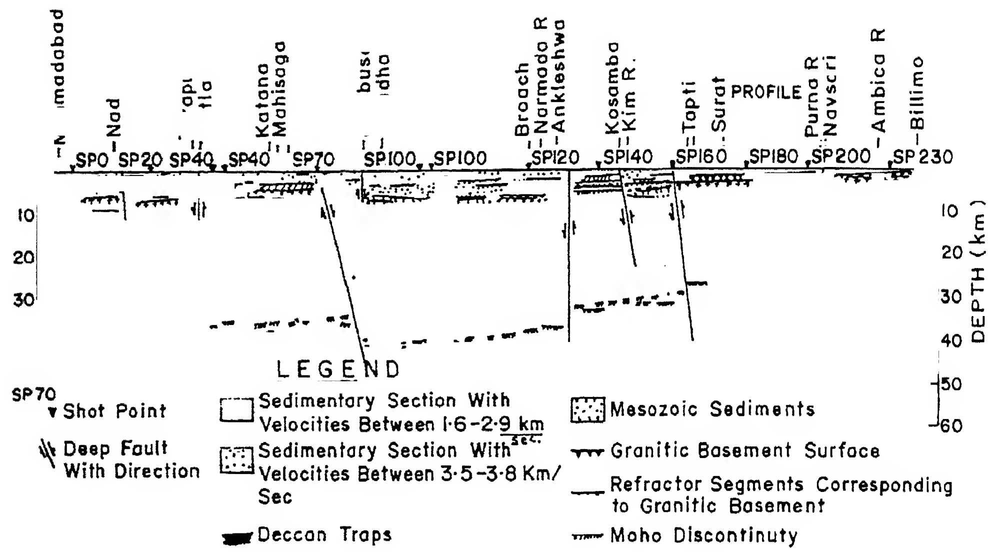
The structural history of the depositional basin since its inception right upto almost Sub-Recent, can be chronologically arranged as under :

i) *Post Mesozoic reactivation of N-S and NNW-SSE Precambrian faults and Narmada Geofracture*

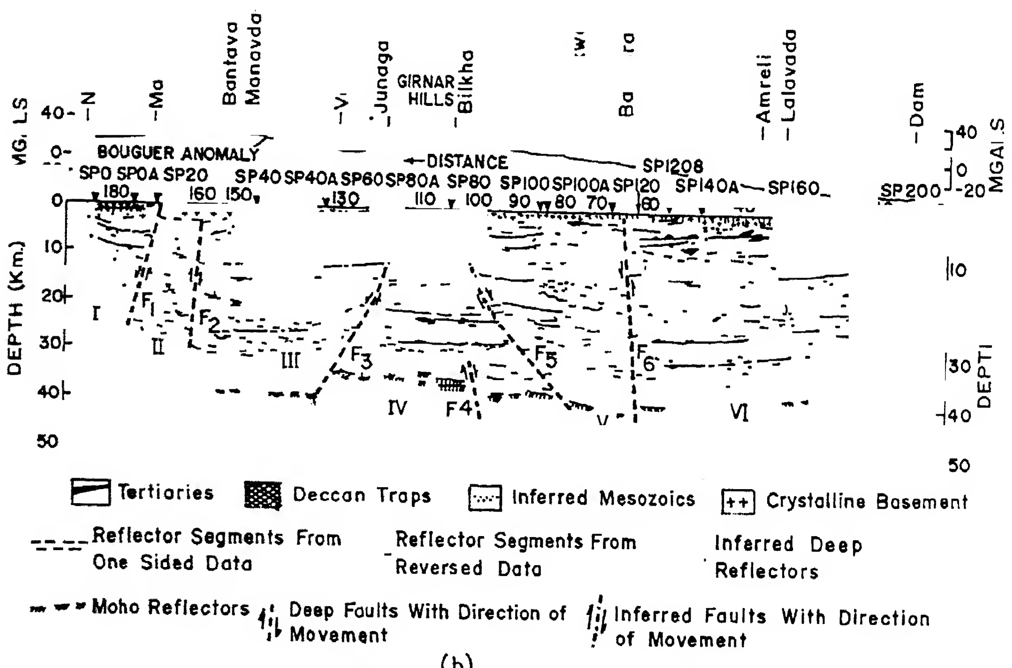
This event gave rise to Cambay Basin a structural depression. This happened at the advent of the Cenozoic. Two regional faults that limited the downfaulted block, have been (delineated by the ONGC, and) referred to as West Cambay Basin Boundary Fault (WMCBF) and East Cambay Basin Boundary Faults (EMCBF) (Fig. 14). Varying trend of these two bounding faults from south to north and even those of the Rajasthan Basin, is a very clear manifestation of the combination of faults with different trends, following one or other directions of fracturing. Whereas smaller faults were responsible for the horst and graben topography of the Cambay Basin basement over which Tertiary sediments were deposited, somewhat larger faults trending NE-SW divided the main basin into 4 sub-basins. Several step faults east of and parallel to EMCBF, also simultaneously developed, thereby providing a wide expanse of low ground, which later on became the site of Quaternary deposition.

ii) *Differential movement along the various faults all - throughout the Tertiary and Quaternary deposition*

Thickness variation and lateral differences in lithofacies in the Tertiary sediments are attributed to this syn-depositional tectonism. Variable thickness of Quaternary deposits in the different structural blocks, indicate continued vertical movement during their accumulation. It however appears that the intensity of this tectonic activity gradually decreased so much. so that during upper Pleistocene and Holocene, it practically died down, or at least considerably reduced.



(a)



(b)

Fig.13 DSS Profiles (A) N-S[34] (B) E-W[35]

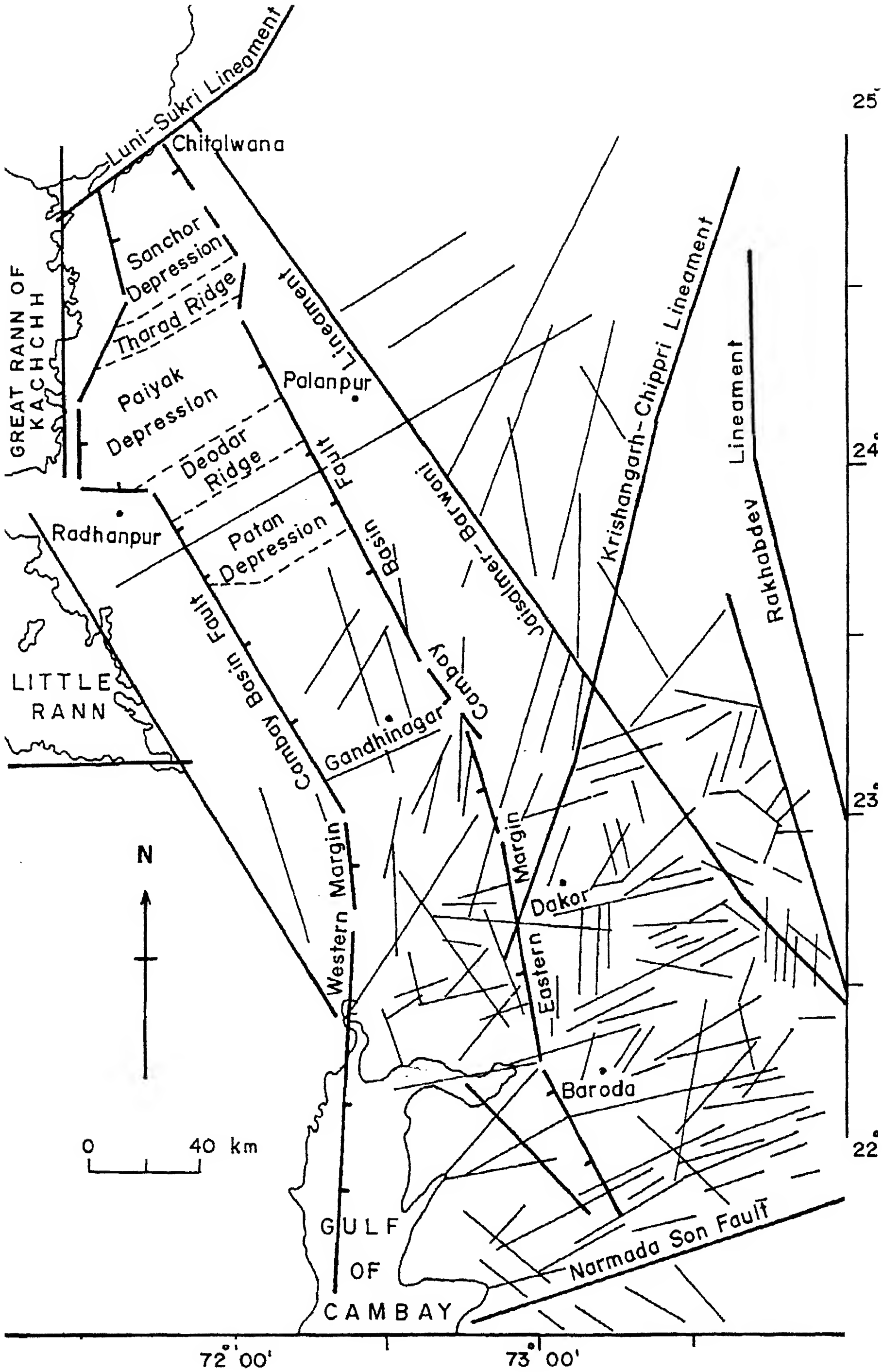


Fig.14 Tectonic map of the alluvial plains with Cambay Basin structure

iii) *During Quaternary E-W to ENE-WSW fracture trends continued to be effective in the manner that they provided preferred directions for the various rivers of the older drainage system*

The older rivers flowing SW to W from the eastern rocky highland impinged into the basin, crossing successively the various step faults finally transected the EMCBF; depositing their debris such that the Quaternary sediments rested over Tertiaries. The older fluvial system (which now stands disrupted), points to a control exercised by the regional westward slope and the E-W to NE-SW fractures. Almost entire part of the sediment thickness (mostly fluvial) was the result of these ancient rivers. The process of fluvial aggradation came almost to a close with the onset of the Terminal Pleistocene aridity.

iv) *Next and the last major phase of tectonic activity took place, sometime in early Holocene, after the aridity*

During this tectonic event, numerous NNE-SSW trending fracture zones developed and these dissected the earlier deposited continental sequence, disrupted the older rivers, deflected their courses, such that Sabarmati and Mahi started flowing along new channels and the Orsang river (relicts of which are seen as the Dhadhar river) instead of flowing due WSW, swung anticlockwise towards Narmada to finally meet it. This phenomenon is very well reflected in the development of vertical cliffs and deeply cut ravines, sinuous channels of trunk stream as well as those of major tributaries. Cliffy channels of Sabarmati, Mahi and Narmada that flow in a zig-zag manner, simulating entrenched meanders, in fact reflect the influence of intersecting or en-echelon fractures that developed during this late tectonism. The rivers flowing along these fractures (mostly joints), in due course have given rise to loops and curves which resemble and behave and look to a certain extent like true meanders, making it difficult to recognise the tectonic control.

All the rivers – Luni, Sukri, Banas, Sabarmati, Mahi and Narmada, show a gentle northwesterly tilt of the newly faulted blocks. As a result, there occur no tributaries on the respective right banks in each case and the smaller streams meet the main rivers along the left banks. Also, the areas to the west of the middle segment of Sabarmati and lower reaches of Mahi, are totally devoid of any drainage and represent uplifted terrain's with a slight NW tilt. Subsurface information also indicates uplift. Obviously, the uplift and tilting were related to this Holocene fracturing.

Lithostratigraphy and Field Description

The Quaternary continental deposits of the Mainland, consist of a succession of layered sediments of marine, aeolian and fluvial origins. A total maximum thickness of over 800m of Quaternary sediments has been computed on the basis of exposed sequences and sub-surface bore hole data. The nature of the base

of Quaternary deposits however is not fully understood and little information is available to delineate the boundary between the Quaternary and the Tertiary.

It may be pointed out that the lower part of the Quaternary sequence remains uninvestigated and the only available information is that provided by Chandra and Chowdhary[37]. These workers of the ONGC have given a Pleistocene age to their Jambusar Formation of Ahmedabad–Mehsana, Cambay-Tarapur and Jambusar-Broach tectonic blocks of Cambay Basin. In the Tharad-Serau block further north, the upper part of Budhanpur Formation has been considered to comprise Lower Pleistocene; or in this formation Pliocene is perhaps gradually changing over to Pleistocene, the entire sequence mostly being fluviatile. In the sub-surface on the western margin of the Cambay Basin in the Dhanduka block (Saurashtra), a conglomerate resting directly over Deccan Trap perhaps represents Lower Pleistocene. In the Viramgam section an undifferentiated sequence resting over the Oligocene Khora Formation could also in part be of Lower Pleistocene age. The agate bearing conglomerates of the coastal areas of Saurashtra and the conglomeratic horizons of the Jhagadia Formation exposed on the Mainland along the eastern margin of the Cambay Basin have been considered as Lower Pleistocene[38].

The base of the huge fluvio-aeolian sequence exposed in the various river sections is a bluish green clay. These clays show well developed rhizocretions and greyish-green drab haloes, indicating sub-aerial activity prior to the deposition of the overlying fluvial sediments. In the subsurface bore-hole data, the Irrigation Department of the Government of Gujarat has shown these clays at the base of the sand-silt-gravel horizons and has erroneously called them as Tertiary marine clays. Merh[38-39] has described them as clays of marine origin deposited during the Middle Pleistocene transgression, stratigraphically comparable with the Miliolites of Saurashtra.

A characteristic feature of these clays is a typical mottled appearance with numerous carbonate tubes, pipes and strings with veins intruding this horizon[28]. These calcrete structures abruptly terminate against the overlying gravels suggesting that they pre-dated the gravel-sand. There was a considerable time gap between the deposition of these clays and that of the overlying gravel; the intervening period giving rise to pedogenetic calcretization. The sequence that overlies these clays and referred to as Gujarat Alluvium[40] and Narmada formation[41] range in age from Upper Middle Pleistocene to Recent. Ideal exposures of the sediments in the major river sections dating back to Middle Pleistocene, have provided a dependable sequential stratigraphy. We identified 40 locations from various rivers and studied them river basin wise. Sequence in each river has been described separately.

Narmada River Basin

Taking into account twelve well exposed lithounit sections along the Narmada river, a composite lithostratigraphic succession has been prepared (Fig. 15 Table

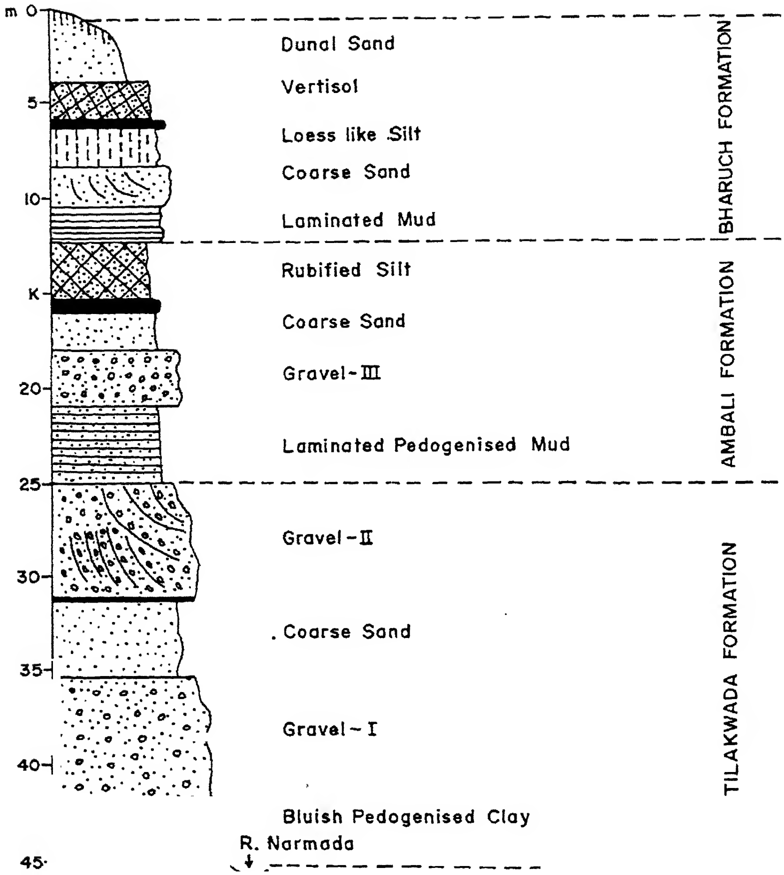


Fig. 15 Lithostratigraphy of exposed continental sediments of Narmada Basin

***Table II** Lithostratigraphy exposed in Narmada River Basin*

THICKNESS	FORMATION	LITHOLOGY
10–12m	Bharuch Formation	Vertisol, Yellowish silty sand through cross-stratified sand. Laminated mud
12–13m	Ambali Formation	Silty sand, Red (rubified) Silty Sand : Coarse Rrddish Sand, Gravel-(III) Laminated pedogenised mud
18–20m	Tilakwada Formation	Coarse Stratified Gravel (G-II) : Stratified/Laminated pedogenised Silty mud, Coarse Reddish Sand; (G-I) Cobbly to Bouldery Inversely Graded Gravel; Bluish Pedogenised Clay/Reddish Brown Mottled Clay

II). Three major stratigraphic formations viz. Tilakwada formation, Ambali formation and Bharuch formation have been recognised.

Tilakwada Formation

The Tilakwada formation marks the base of the total exposed Quaternary sediment succession in the Lower Narmada valley and comprises five major horizons—*(i)* bluish pedogenised and mottled clay, *(ii)* cobbly to bouldery gravel (Gms- facies/ Gravel-I), *(iii)* coarse reddish sand, *(iv)* Laminated/stratified pedogenised silty mud and *(v)* cross-stratified gravel (Gp-facies/Gravel-II).

The bluish pedogenised clay forms the base with an exposed thickness of 2 to 3m and is overlain by a poorly sorted 5 to 6m thick horizon of cobbly to bouldery gravel (G-I); it shows inverse grading at places. It is ideally exposed at Tilakwada and Rampura. The gravels are overlain by sand-sheets (Fig. 16) and trough cross-stratified beds of around 4m thickness; these at places are replaced by stratigraphic equivalent units of laminated mud. Above this horizon, cross-stratified gravel of about 5 to 6m in thickness (G-II) is encountered; this gravel at places shows planar cross-stratification.

Ambali Formation

The Ambali formation overlies the gravel (G-II) and ranges in thickness between 13 and 15m. It comprises 4 major units; *(i)* laminated pedogenised mud; *(ii)* sandy gravel (Gravel-III) (Fig. 17); *(iii)* silty sand and *(iv)* rubified silty sand. The pedogenised laminated mud, 4m thick, directly rests over Gravel-II and is devoid of any sedimentary structure. The mud is overlain by 3m thick sandy gravel (G-III). Silty sand of about 2 to 2.5m thickness overlie this horizon, which at places is replaced by a stratigraphically equivalent unit of pedogenised mud. The topmost part of this formation is a 3 to 4m thick silty sand which is brownish red in colour. More or less, structureless, this rubified unit is at places demarcated from the underlying silty sand horizon by a concentration of calcretic layers.

Bharuch Formation

This formation forms the upper portion of the Narmada succession, and has a thickness range of 10 to 12m. It is made up of five major units, viz. *(i)* weakly pedogenised laminated mud; *(ii)* pedogenised silty sand; *(iii)* pale yellow coloured silt (loess-like); *(iv)* pedogenised silt and *(v)* fine dunal sand. The weakly pedogenised laminated mud unit (1.5-2m) forms the base of the formation, and rests over the rubified horizon of the Ambali formation. The mud, at places is seen to change over laterally to trough cross-stratified sand. This laminated mud/cross-stratified sand is overlain by 2 to 3m thick fine loess-like silt, which is structureless and easily recognised by yellowish buff colour. This succession is finally capped by a aeolian sand horizon of 2 to 4m thickness, which has given rise to a characteristic typical dunal topography.

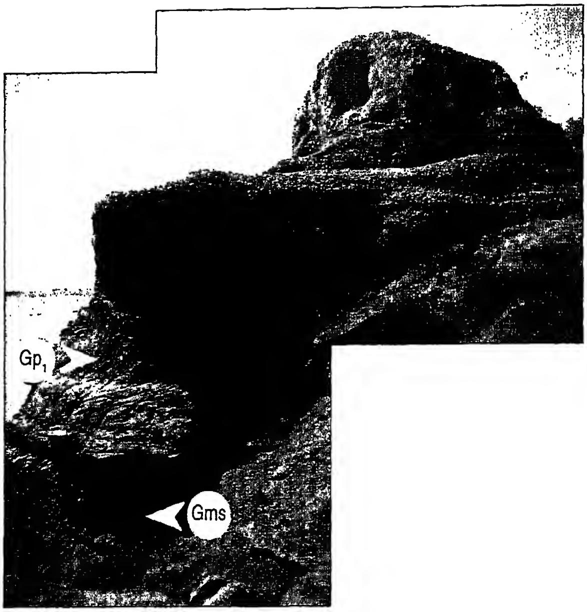


Fig.16 View of exposed Quaternary sediment succession at Tilakwada, the gravels are overlain by sand sheets and trough cross-stratified beds

Fig.17 Close-up view of cross-stratified gravel at Ambali

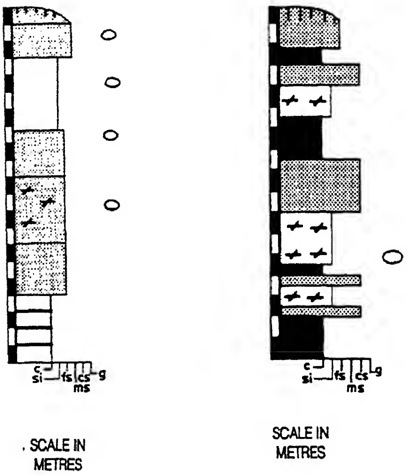
LEGEND

GRAVEL	CALCRETE	RHIZOLITHS
SAND	PEDOGENESIS	CLAY LENSE
SILT	PLANAR CROSS-STRATIFICATION	TROUGH CROSS-STRATIFICATION
CLAY		

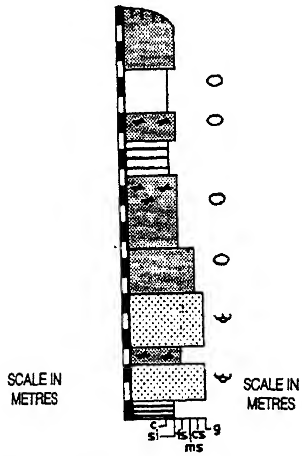
Br fm	Bharuch formation
Am fm	Ambali formation
Ti fm	Tilakwada formation
Si fm	Singrot formation
Sh fm	Shihora formation

Ra fm	Rayka formation
Tm	Timba member
Phm	Phajalpur member
Dam	Dabka member
Dom	Dodka member

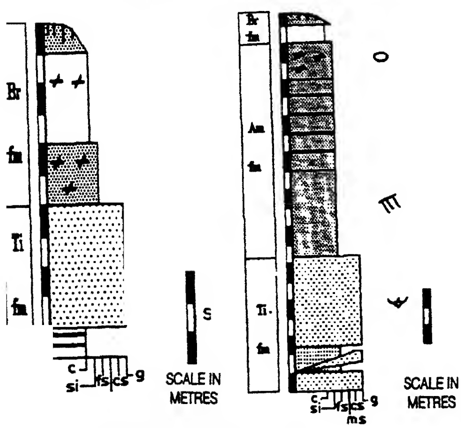
Am fm	Angadh member
Pom	Poicha member
Vam	Vasad member



Bharuch & Nikora Sections



Kanjetha & Ambali Sections



Sankheda & Chandod Sections

Locationwise Description

Bharuch Section

This section is located on the right bank of Narmada, 25km upstream from the mouth. The exposed cliffs in this area range in height between 18 and 20m and show only the Bharuch formation which is represented by fluvial silts and the uppermost aeolian sand.

Nikora Section

This is located 10km upstream of Bharuch on the right bank of the Narmada. The section varies in thickness from 17 to 18m. The basal pedogenised clay is followed by the Ambali formation (12m) and capped by the laminated mud and dunal sand of Bharuch formation (3m). Tilakwada formation except the basal clay is absent at this location.

Kanjetha Section

This section is located 8km upstream of Nikora on the right bank. The section height varies between 28 and 30m. It begins with Tilakwada formation (10m) and is overlain by Ambali formation (12m). The youngest is the Bharuch formation and is 6m thick.

Ambali Section

This section located 12km upstream of Kanjetha on the right bank of Narmada is 20 to 22m thick. The Tilakwada formation (7m) marks the base; in turn it is overlain by 8m thick Ambali formation. This unit is followed upwards by the Bharuch formation and is 7m thick.

Sankheda Section

The section is located 15km upstream of Chandod on the left bank of Orsang river. The cliff height here ranges between 12 and 14m. The basal part is represented by 7m thick Tilakwada formation, Ambali formation is absent and the Bharuch formation (5m) directly overlies the Tilakwada formation.

Chandod Section

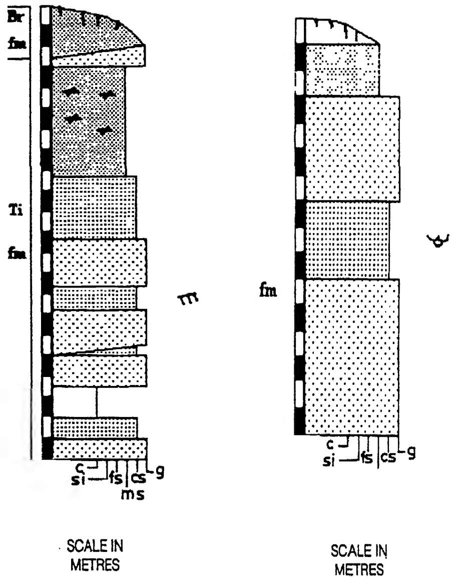
A more or less complete sequence is seen in this section, exposed on the left bank of the Orsang river at its confluence with the Narmada. The cliff height is around 18m and the section comprises Tilakwada formation (7m), Ambali formation (6m) and Bharuch formation (5m).

Tilakwada Section

This section is exposed at the confluence of the rivers Men and Narmada. The 25m left bank section is represented by 20m thick Tilakwada formation overlain by 5m of Bharuch formation.

Rampura Section

Located upstream of Tilakwada on the left bank of Narmada, the 19m section is made up of a lower 15m thick Tilakwada formation, followed upwards directly by 4m thick Bharuch formation represented by aeolian sediments.



Tilakwada & Rampura Sections

Mahi River Basin

The Mahi river provides very good sections all along its course, and on the basis of the exposed lithounits studied at 10 locations, a composite stratigraphy could be prepared (Fig. 18; Table. III). The exposed sequence (Fig. 19) resting over the basal clays, has been divided into three formations viz, Rayka, Shihora and Singrot.

Rayka Formation

The Rayka formation is seen to rest over the basal clays and shows an overall thickness of 10 to 11m. The formation is made up of two members :

(a) Vasad Member; and

(b) Poicha Member

Vasad Member

The Vasad Member has an average thickness of 8 to 9m and consists of three units. It directly overlies the basal clay; good outcrops are seen at Vasad and Rayka. The three units consist of *(i)* planar to epsilon cross-stratified gravel (Gp/Gt facies), the clasts being mainly basaltic and calcretic (2 to 2.5m), *(ii)* overlying stratified silts and calcrete (marly) bands (Fl facies) of about 3 to 4m which at

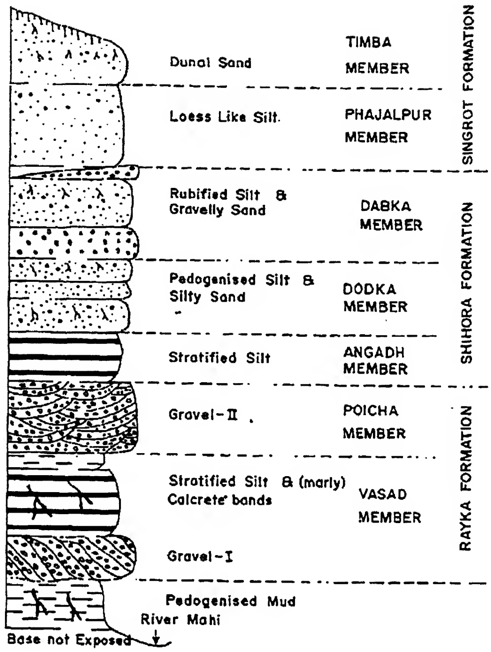


Fig. 18 Lithostratigraphy of the exposed continental sediments of Mahi Basin

***Table III** Lithostratigraphy exposed in Mahi River Basin*

FORMATION	MEMBERS	LITHOLOGY	ENVIRONMENT	AVERAGE THICKNESS (m)
Singrot Formation	Timba member	Dunal sands	Aeolian	2 - 3
	Phajalpur member	Loess like silts	Aeolian	3 - 4
	Dabka member	Red (rubified) soil with calcrete nodules, Reddish gravelly sand	Fluvial	5 - 6
Shihora Formation	Dodka member	Brown pedogenised and yellowish	Fluvial	8 - 9
	Angadh member	Silty sand alongwith calcrete nodules Alternate silts and sand horizon alongwith calcrete layers	Fluvial	3 - 4
	Poicha member	Trough cross-stratified gravel-II comprising quartizitic, basaltic and caliche clasts.	Fluvial	2 - 5
Rayka Formation	Vasad member	Pedogenised fractured mud (Vertisol ?), Fine silty sand, Stratified silts and calcrete (marly) bands, Planar to Epsilon cross-stratified gravel-I comprising basaltic and caliche clasts.	Fluvial	8 - 9
		Pedogenised mud with rhizocretions and drab haloes.	Marine	2 - 3

Fig. 19 View of exposed Quaternary sediments succession at Rayka

places shows distinct warping and *(iii)* uppermost 1 to 1.5m thick pedogenised fractured mud (vertisol).

Poicha Member

The Poicha Member overlies the Vasad member and consists of trough cross-stratified gravel (Gt facies, Fig. 20) consisting chiefly of clasts of basalt, calcrete and some quartzitic fragments. The average thickness of this member ranges between 2 to 5m and it is very well exposed at Vasad, Rayka, Bhadarwa and Poicha.

Shihora Formation

The Shihora formation (Fig. 21) comes above the Rayka formation and consists of three members viz.

(a) Angadh Member;

(b) Dodka member; and

(c) Dabka Member

Fig.20 Trough cross-stratified gravel at Poicha

Angadh Member

The Angadh member rests over the Poicha member of Rayka formation, is 3 to 4m in thickness and consists of thick alternate silts and sands alongwith calcrete layers (Fl facies) that are developed predominantly along the silty horizons.

Fig. 21 Left bank cliff section at Shihora

Dodka Member

The Dodka member is made up of two brown pedogenised silty sand horizons with an intervening yellowish silt. Thickness of the member ranges between 8 and 9m. The two brown pedogenised horizons are well exposed at Vasad, Rayka, Poicha and Shihora but the best exposure is at Dodka, both the horizons show a conspicuous concentration of calcrete nodules in their upper parts.

Dabka Member

This member is a marker horizon that separates the fluvial sediments from the overlying aeolian sediments, and consists of a conspicuous red pedogenised silty-sand bed. This rubified horizon with a thickness of 5 to 6m is well exposed at Dabka, Angadh, Vasad, Rayka, and Dodka.

Singrot Formation

This formation mainly comprises aeolian sediments resting over the fluvial sequence of the underlying Dabka member of the Shihora formation. The Singrot formation is divided into two members.

(a) Phajalpur Member; and

(b) Timba Member

Phajalpur Member

This member is made up of fine silts and shows typical structureless vertical pale yellow bluffs with abundant calcrete nodules found embedded randomly. The grain size data shows about 50-60% of silt content and the appearance is "loess-like". This member has a thickness range of 3 to 4m and is exposed almost uninterruptedly all along the river valley.

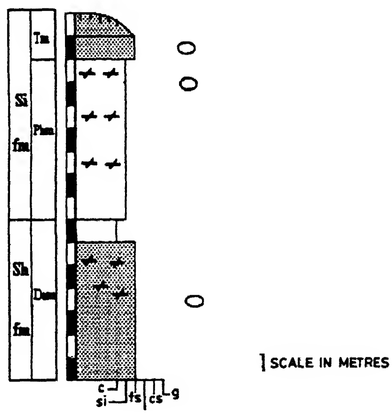
Timba Member

Timba member overlies the loess-like silts, capping the entire fluvial sediment sequence. Made up of silty sand, has a thickness of 2 to 3m and shows a typical dunal topography. Pedogenesis is noticed in most sections which has given rise to a marked stabilization of this horizon. This phenomenon has led to the preservation of dunal topography in the Mahi environs.

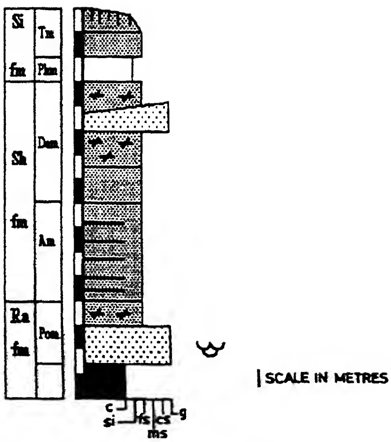
Locationwise Description

Dabka Section

Located near the mouth of the Mahi river on the left bank, this section has a cliff height of 12m. The section shows well developed exposures of the Dabka member (4m) of the Shihora formation; the Dodka and the Angadh members are absent. The Dabka member is overlain directly by the Phajalpur member (5-6m) of the Singrot formation. The Phajalpur member shows conspicuous features of pedogenesis; it is capped by the Timba member.



Dabka Section



Angadh Section

Rayka Section

Singrot Section

This section located on the right bank, 20 km west of Baroda has a cliff height of 15m. The exposed section shows stratified silts (3.5m) of Vasad member overlain by Poicha member (1.5m) of Rayka formation. The Angadh and Dodka members of Shihora formation are absent. The Dabka member has a thickness of 4.5m and overlies the Rayka formation. 5.5m thick Singrot formation alongwith its constituent members overlies the Shihora formation.

Angadh Section

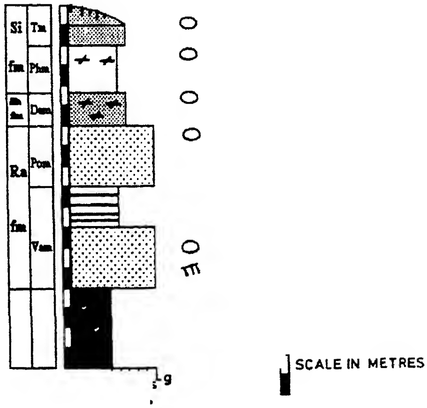
Located 4km south of Vasad, the cliff height of the section on the left bank of the river is 15m. The exposed section shows the basal clay over which rests the Rayka formation, a formation absent at Dabka. The Vasad member is absent and the Poicha member (1m) rests directly over the basal clay. The Poicha member is in turn successively overlain by Angadh member (5m) the Dabka member (3m) of Shihora formation. Dodka member is absent and a 3m thickness of Singrot formation caps the sequence.

Rayka Section

This section by far provides the best exposure and more or less a complete succession. Located 26km NW of Baroda, at Rayka, the 36m left bank section displays all the formations and their constituent members. The base of the sequence is the usual pedogenised horizon (basal clays) over which comes the Rayka formation; its both members, Vasad (8m) and Poicha (2m) are very well exposed. The Rayka formation is overlain by the Shihora formation and all its three members, Angadh (2m), Dodka (8m) and the Dabka (5.5m) are present. The topmost Singrot formation with its both members, Phajalpur (3.5m) and Timba (2m) completes the sequence at this locality.

Vasad Section

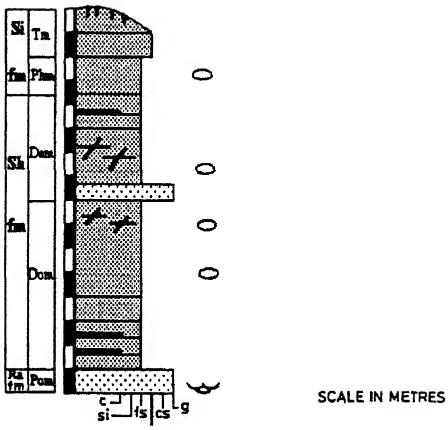
Vasad is located 23km northwest of Baroda, and shows a left bank cliff section of 18 to 20m. The sediment succession is more or less identical to the Rayka section, except that here, the Angadh member and the reddish gravelly unit of Dabka member of Shihora formation are absent.



Vasad Section

Dodka Section

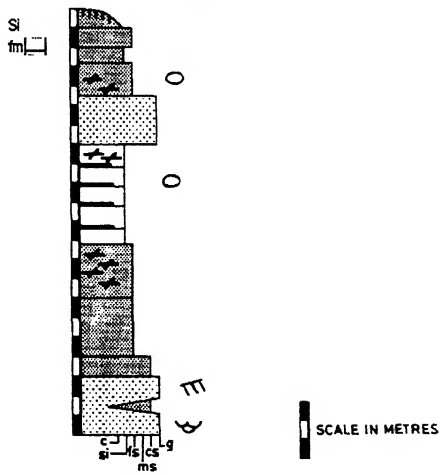
Dodka is located 2.5km upstream of Rayka and has an exposed section of 15m. Broadly it forms an extension of the horizons exposed at Rayka. The basal pedogenised clay however is absent, and the sequence commences with the Poicha member (1m) of the Rayka formation at the base. The Shihora formation overlies the Rayka formation which consists of the Dodka (7m) and Dabka (4.5m) members; the Angadh member is absent. The Singrot formation with its two members Phajalpur member (1.5m) and Timba member (2m) overlies the Shihora formation.



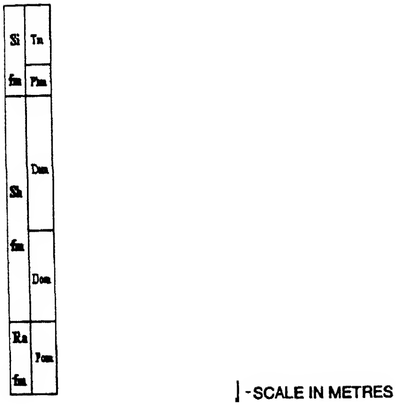
Dodka Section

Poicha Section

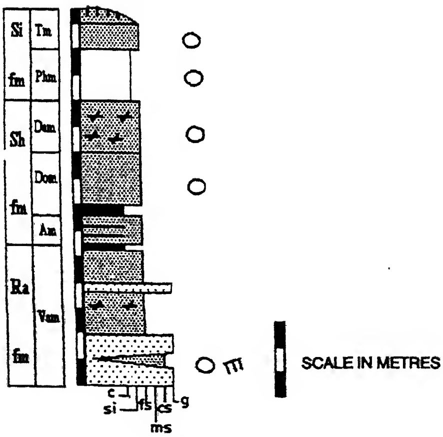
Located on the left bank of the river near Savli, the 22m thick exposed sequence rests directly over trappean basalts. The sequence commences with Poicha member (4m) of the Rayka formation, which is overlain successively by the Angadh member (11m) thick and the Dabka member (4m). The Dodka member is not observed here. The overlying Singrot formation has a total thickness of (3m) and is made up of 1m thick Phajalpur member and 2m thick Timba member.



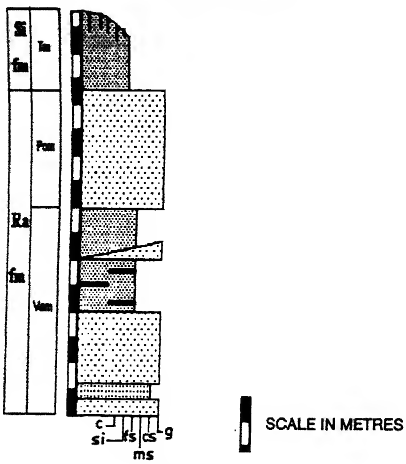
Poicha Section



Shihora Section



Timba Section



Kadana Section

Shihora Section

On the left bank of Mahi, 12km SE of Dakor at Shihora the section shows a sediment succession of 18m resting over agglomeratic flows of trappean basalt. The Poicha member (3.5m)of Rayka formation is overlain by the Dodka member (4.5m). The Dabka member overlies the Dodka member, is 6.5m thick and is dominated by reddish gravels, the clasts of which show reddening due to a ferruginous coating. It is overlain by the Phajalpur member (1.5m). The Timba member (3m) forms the topmost part.

Timba Section

At Timba, the sediment succession of 15m rests over Trappean basalts. The section directly begins with the Vasad member (5.5m). The Poicha member is absent and the overlying Shihora formation begins with a 1m thick Angadh member followed upward by the Dodka member (2.5m) and Dabka member (2m) respectively. The Singrot formation has an aggregate thickness of 3.5m and consists of both Phajalpur member (2m) and Timba member (1.5m).

Kadana Section

This section is exposed in the river SE of Kadana reservoir on the left bank. This is the only site where the sediments are seen directly resting over Precambrian quartzites. The sediment succession has a thickness of 12 to 15m. The section here begins with the Vasad member (4.5m), overlain by 4-5m thick Poicha member of Rayka formation. The Shihora formation is absent. The Timba member (2m) of Singrot formation directly comes over the Poicha member, the Phajalpur member being absent.

Sabarmati, Rupen, Khari, Saraswati, Banas and Luni River Basins

The Sabarmati river provides very good cliff sections revealing almost entire exposed sequence whereas the rivers further north show only the upper part of the succession. On the basis of a critical appraisal and synthesis of information obtained from a number of exposed sections in the Sabarmati, Rupen, Khari, Saraswati, Banas and Luni, supported by sub-surface bore-hole data, a composite stratigraphy for these northern rivers has been worked out (Fig. 22; Table IV).

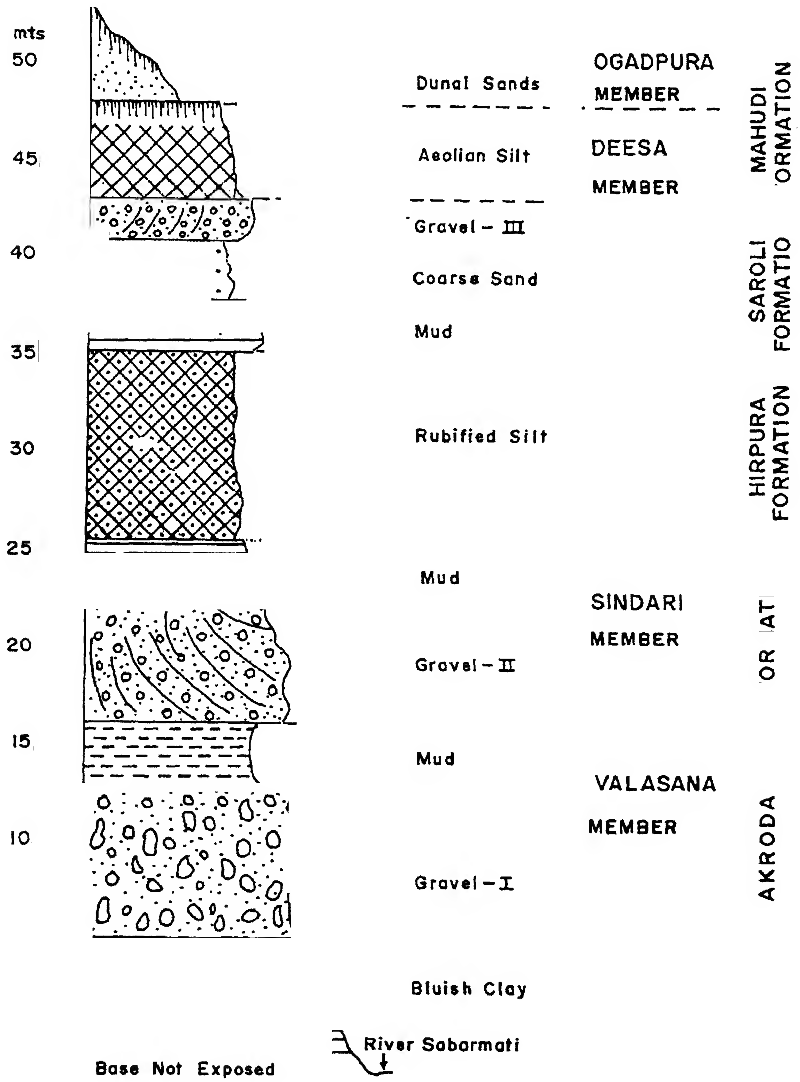


Fig.22 Integrated lithostratigraphy of Sabarmati and other North Gujarat rivers

Table IV Integrated stratigraphic record of North Gujarat (Sabarmati to Luni)

FORMATION	MEMBER	LITHOLOGY	DEPOSITIONAL ENVIRONMENT	AVERAGE THICKNESS (M)
MAHUDI FORMATION	Ogadpura Member	Dunal sands, fine grained with quartz and mica flakes. No sedimentary structures	Aeolian	
	Deesa Member	Fine to medium grained silt, loess-like, structureless, porous, homogenized and stabilised.	Aeolian	
SAROLI FORMATION		Coarse sand and mud with lenses of gravel, chiefly comprising quartz grains, felspar and rock fragments with interlayering of silt, sand and mud. Gravel lenses show cross bedding.	Fluvial	10
HIRPURA FORMATION		Red, reddish brown silt, unconsolidated, composed of subangular quartz grains. Calcareous nodules present in the basal part, concentration increasing downwards.	Fluvial	8-10
LAKRODA FORMATION	Sindari Member	Gravel, consolidated comprising quartzite's felspar in a calcium carbonate matrix. Stratification well preserved. Cross bedding visible.	Fluvial	8-10
		Overlain by laminated mud, chiefly comprising fine grained quartz.		
	Valasana Member	Gravel, consolidated with clasts of quartzite's quartz, granite, agate, chert, jasper and other rock fragments. Overlain by fractured mud, chiefly made up of quartz and mica flakes.	Fluvial	5-8
		Bluish green clay mottled, with carbonate, tubes, veins and strings.	Marine ??	

Lakroda Formation

Lakroda formation rests directly over the blue clays with a total thickness of about 15 to 20m consists exclusively of fluvial sediments. The formation has been divided into two members

(a) *Valasana Member;* and

(b) *Sindari Member*

Both the members are fluvial in origin but are clearly divisible into two well defined and distinct fluvial depositional cycles. The Valasana member can be traced in Sabarmati from Valasana in the north to Sadra in the south, while the gravels of Sindari member are noticed all throughout the rivers of North Gujarat, and also occur in the sub-surface.

Valasana Member

The Valasana member has a very conspicuous basal gravel (G-I) overlain by a fractured mud horizon. The transition is gradual and the gravel upwards changes

over to a gravelly grit and sand with clasts of varying sizes. This unit is best developed in the proximal end near Valasana where it shows maximum development of 8m thickness which progressively decreases downstream. At Lakroda, this horizon again appears as a lens with a maximum thickness of 5m before finally terminating downstream near Oran. The topmost part of this member is a 3m thick layer of mud, whose contact with the underlying gravelly horizon is rather sharp. The mud layer does not show much of lamination, but is characteristically fractured both horizontally as well as vertically. This horizon which represents fine fluvial sediments points to its deposition under tranquil conditions. It is dark brown in colour and shows some pedogenesis.

Sindari Member

The gravelly rocks (G-II) of this member whose thickness varies from 8 to 10m are quite distinct from those of Valasana member. The clasts are mostly pebbles of smaller size and the entire member is compacted by a calcareous cement and shows well defined cross-stratification (Fig. 23). Comparable deposits are also seen in the Banas and Sabarmati rivers. In Sabarmati, good exposures are met all along the cliff sections. The cross-stratification is quite pronounced in the upper reaches of the Sabarmati. Downstream beyond Sadolia, this structure tends to change over to almost horizontal sheets. The top portion of this member is again

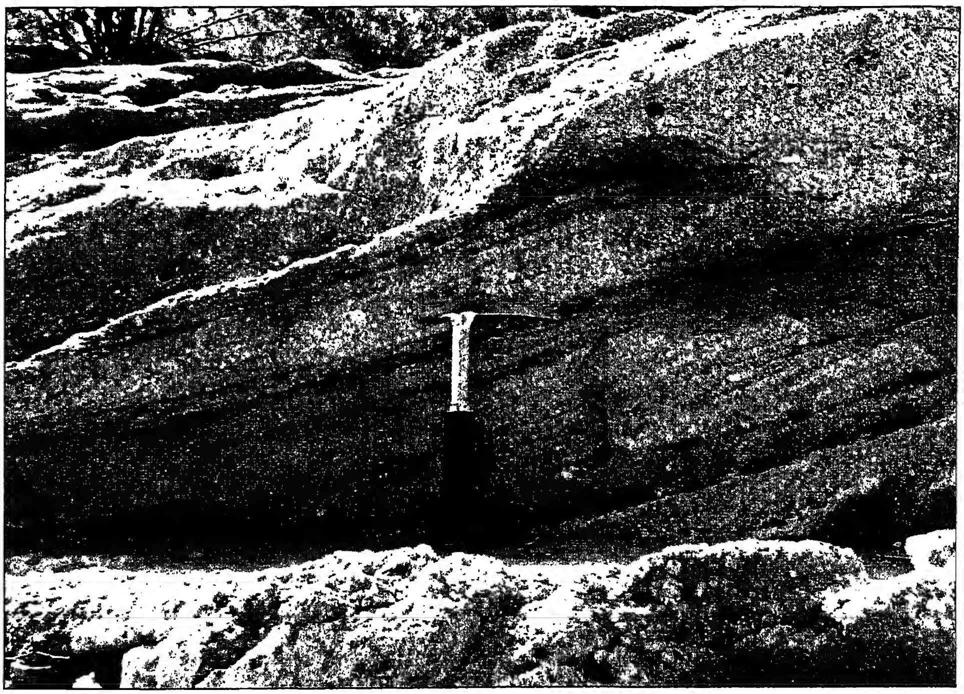


Fig.23 Close-up view of planar cross-stratified gravel at Sindari

a mud layer, light yellow in colour and shows distinct lamination. This mud does not show any signs of pedogenesis. The presence of lamination within this horizon indicates the changing velocity of the currents depositing the mud resulting in fine layering. This mud is not seen in Luni and Banas rivers where the gravels directly underlie the dunal sands of youngest Mahudi formation. In Sabarmati river however it shows a good development and is seen as a 3m thick almost continuous horizon between Mahudi to Sadra.

Hirpura Formation

This one member formation overlying the Sindari member comprises all-throughout an important and very conspicuous sandy silt horizon. The formation derives its name from the village Hirpura on the Sabarmati river where it has attained a thickness of 10m and is very conspicuous by its red coloration (Fig. 24). It is exposed all along the Sabarmati valley forming a 8-10m thick band. The formation is also exposed in Banas river (Deesa section) but has been only partly exposed in the smaller rivers like Rupen and Pushpavati. Its presence is also recorded in the bore-hole data.

Fig.24 View of rubified silts at Hirpura

Saroli Formation

The Saroli formation again marks the onset of a fresh fluvial depositional cycle as it rests with a very distinct non-conformity indicated by a sharp contact and sudden change in sediment nature. This formation is best exposed in the cliffs of Sabarmati river at Saroli, where all the units of this formation are encountered attaining a thickness of 10m. Other good exposures of this are in the downstream at Mahudi, Lakroda, Oran and Madhavghat. The entire sequence points to a progressive increase in the depositional energy, the grain size progressively coarsening upward. Based on the grain size and lithology the sequence is divisible into three units. The lowermost mud layer rests over the Hirpura

formation. There is upward coarsening which changes the mud layer into a horizon of coarse sand. The mud horizon occurs as lensoid bodies and is seen only near Valasana and again around Saroli. No traces of this horizon are found downstream of Saroli. The coarse sand horizon which overlies the mud unit is also lensoid in nature and occurs in the proximal end at Valasana, again appears as a lens at Kot before disappearing at Vijapur. The transition of mud to coarse sand is rather gradual and with the disappearance of mud, the sands come in direct contact with the underlying formation. The sands merge upward into a gravelly unit. Within the sands occur thin lenses of gravel. With the sudden appearance of aeolian silts that overlie this formation, a distinct and abrupt climatic change is visualised. A near total absence of pedogenetic features in this formation indicates a sudden onset of aridity and deposition of wind blown material without any time interval.

Mahudi Formation

This formation is the youngest one and overlies the older fluvial sediments. In the Sabarmati river section, it shows good exposures at Mahudi and has therefore been named Mahudi formation, the formation has been divided into two members :

(a) *Deesa Member* and

(b) *Ogadpura Member*

Deesa Member

This member essentially consists of wind blown fine sand and silt deposited during the major arid phase that set in during the Terminal Pleistocene. It shows a prominent development north of Sabarmati and forms a sheet-like body of variable thickness, the average maximum being 5m, and is characterised by a very contrasting dunal topography. The dunes rise as high as 25m above the ground level. Beyond Banas towards Luni the topography is a reflection of this member and the entire landscape forms an undulating hummocky surface with occasional clusters of very high dunes (Diodar Δ73m, Tharad Δ59m, Khundala Δ63m and Vav Δ43m). A diagnostic feature of this member is the ubiquitous stabilisation, pedogenesis and calcretisation, and a vegetal cover. Khundala on the Luni river offers a very good example where development of layered calcretes is recorded.

Ogadpura Member

This member represents the unconsolidated recent material spread unevenly over the Deesa member. It is best developed in the area between Banas and Luni. At many places, it is seen resting directly over the gravels and sands of the Saroli formation. Further north, beyond Luni, the member merges into the unconsolidated sands of the Thar Desert. Occurring as discontinuous sheets of loose to consolidated sand sheets, dunes and ridges, it provides a good example of the present-day desert topography. The deposits do not show any pedogenetic changes except that due to the periodic fluctuations in seasonal rainfalls, locally some vegetation

has grown and provided some stabilisation. The constituent material of this member is more or less identical to that of the Deesa member except that it tends to be slightly coarser, more friable and devoid of calcretes.

Localitywise Description

Sabarmati River

Valasana Section

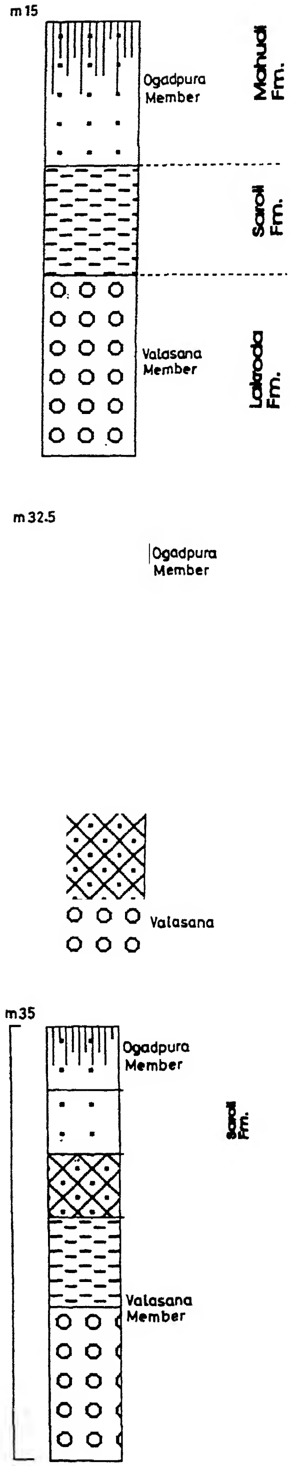
Valasana is located 18km SSE of Kheralu and has an exposed cliff section of 15m. The section here has been considered as the type section for the Valasana member (6m) of the lowermost Lakroda formation. However, in this section, the entire Hirpura formation, the Deesa member of the Mahudi formation and the Sindari member of Lakroda formation are absent. Lakroda formation is represented here by the Valasana member only and the Gravel-I unit forms the base of the exposed sequence.

Kot Section

Located 25km downstream of Valasana, the Hirpura formation (6.5m) is encountered for the first time at this location. The Deesa member and Sindari member of Mahudi and Lakroda formations respectively are not represented. The Valasana member (Gravel-I, 5m) forms the base.

Kadoli Section

Kadoli is situated 20km NNW of Himatnagar, and the section here shows a sequence similar to that at Kot except that the Valasana member (10m) is fully represented with both the units viz, Gravel-I and the fractured mud. The gravel has a thickness of 7m and is highly compacted, with streaks of red colouration.



Valasana Section

Kot Section

Kadoli Section

Aglod Section

The Aglod section, 33km from Vijapur is conspicuous for the first appearance of the cross-stratified Gravel-II unit of the Sindari member (8.5m), a member which is fully exposed here. Valasana member (9.5m) forms the base while the rubified silts of Hirpura formation (5.5m) are seen directly underlying the topmost dunal sands.

Hirpura Section

The type section of Hirpura formation is located 17km from Vijapur. The most conspicuous feature of this section is thick horizon (9m) of rubified silts. This section represents a comparatively better developed Sabarmati Quaternary sequence where all the formations are exposed.

Vijapur Section

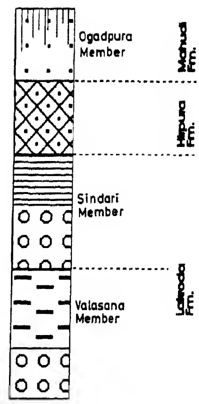
At Vijapur, further downstream, the Hirpura section continues, and the cliff sections, except for the disappearance of the laminated mud unit of Sindari member, are identical. The base of the sequence at Vijapur though is the clay horizon.

Bheempura Section

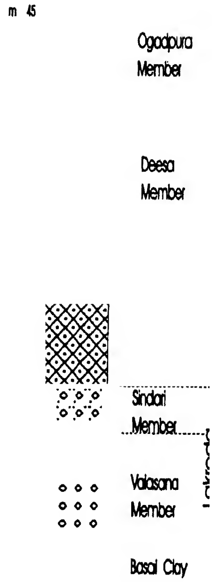
The Bheempura section located in the ravines of the area around the village Bheempura, 8km SSE of Vijapur has the Valasana member (mud unit, 2.2m) of the Lakroda formation exposed in the lowermost part. The Saroli formation (3.5m) is poorly represented, while both the members of the Mahudi formation (6m) show good development.

Saroli Section

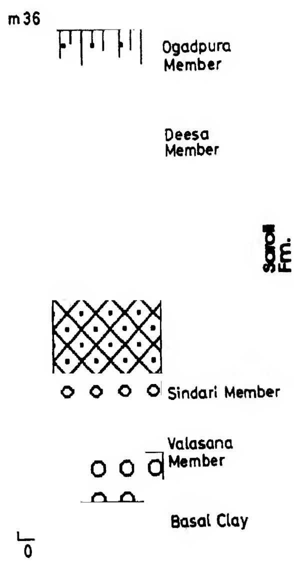
Further downstream, at Saroli, 18 km SSW of Himatnagar, the cliffs provide



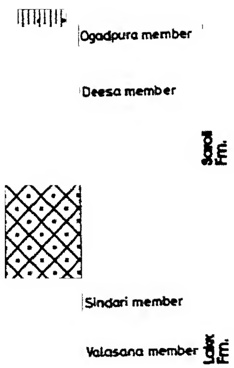
Aglod Section



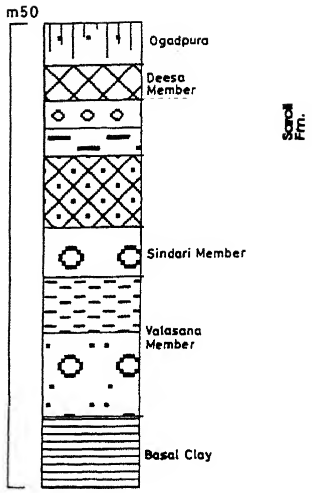
Hirpura Section



Vijapur Section

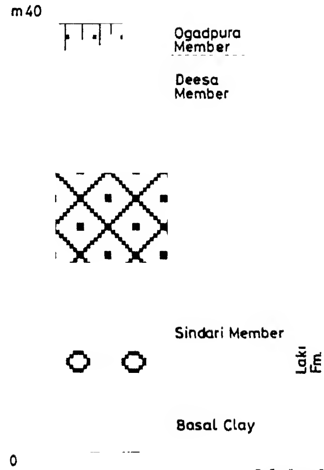


Bheempura Section



Saroli Section

the type section for the Saroli formation and present a very good view of the Sabarmati river with heights of ~50m representing probably the best and most complete sequence exposed along the entire course of the river. The base of the section is the usual bluish green mottled clay horizon. It is here only that in addition to the Lakroda and Hirpura formation, the coarse sandy cross bedded gravel (Gravel-III, 2.5m) unit of Saroli formation is exposed. The laminated mud unit of the Sindari member of the Lakroda formation is absent here suggesting its occurrence at Kot and Aglod as a lensoid body only.



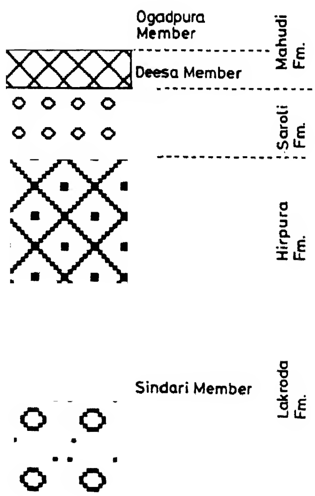
Mahudi Section

Mahudi Section

The type section of the Mahudi formation is seen at Mahudi, 32km from Gandhinagar. The sequence here forms a massive cliff, and the section is marked by the disappearance of the entire Valasana member, due to which the Gravel-II unit of Sindari member (6m) is seen directly resting over the basal clay horizon.

Sadolia Section

Located 5km downstream of Mahudi, the only notable aspect of this section, apart



Sadolia Section

from the continuity of the Mahudi sequence is that the Gravel-III unit (4.5m) of Saroli formation is seen directly overlying the rubified silts of the Hirpura formation, the intervening laminated mud being absent.

Lakroda Section

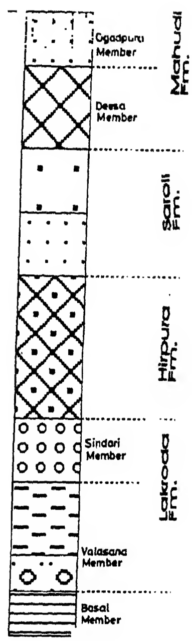
Lakroda, 7km from Mahudi offers a cliff section which along with the Saroli section represents the two best exposed sequences of the Sabarmati river cliffs. The most important feature of the Lakroda section is the reappearance of the Valasana member (7.5m) here, though its nature is somewhat different from its earlier counterparts upstream in the proximal source of the river (Valasana, Aglod, Kot). The Gravel-I unit is highly compacted, massive and has a finer grain size unlike the pebbly coarse compacted gravel of this horizon upstream. Except for the absence of the mud unit of Saroli formation, this section also provides the complete exposed sequence in the entire Sabarmati river. The Lakroda formation (12m) derives its name from the best developed exposures of the two constituent members viz.,the Valasana and Sindari members, at this locality.

Oran Section

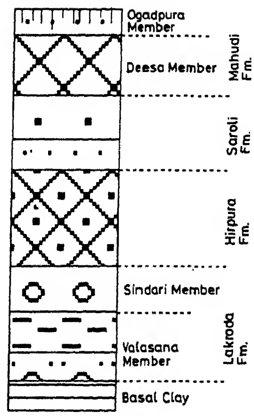
At this locality, 20km from Prantij, the Gravel-I unit (3.5m) of the Valasana member (6m) has a sheet-like appearance and is quite thick. All the other formations are also present here, though none are complete. The Hirpura formation (8.5m) is very prominently developed here and is visible from a long distance.

Madhavghat Section

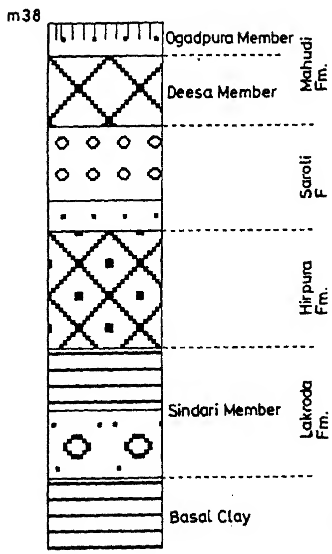
At Madhavghat, 5km upstream of Sadra, the Valasana member is absent and the gravels of the Sindari member (9.75m)



Lakroda Section



Oran Section

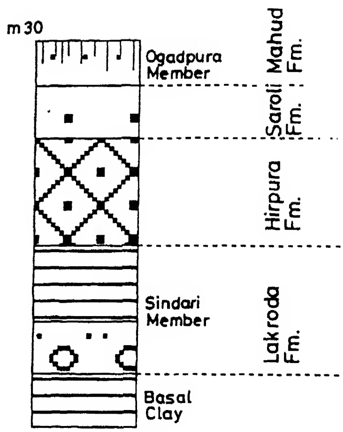


Madhavghat Section

directly rest over the basal clay horizon. The absence of Valasana member here and its appearance at Oran and Lakroda points to its occurrence only as a lensoid body in the downstream channel.

Sadra Section

Sadra 18 km from Gandhinagar represents the last exposed section that shows good exposures of the Sabarmati sequence. The aeolian silts of Deesa member and the Valasana member of Mahudi formation and Lakroda formation are absent. The Sindari member (10m) is seen directly resting over the basal clay horizon.

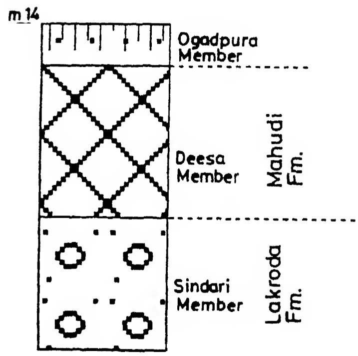


Sadra Section

Rupen River

Modhera Section

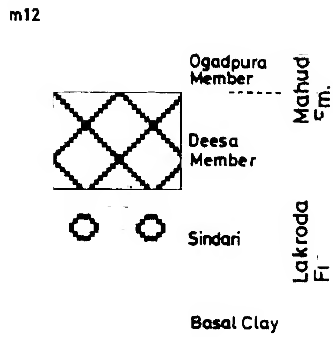
At Modhera 25 km NE of Bechraji, the section shows the gravels (Gravel-II, 5,5m) of Sindari member at the base over which lies the Deesa member in turn, capped by the Ogadpura member of Mahudi formation (9.5m).



Modhera Section

Sankesh Section

Sankesh, 25 km east of Modhera has an exposed cliff of 12m. The sequence is similar to that of the Modhera except that the Sindari member (3.5m) rests directly over the basal clay horizon.

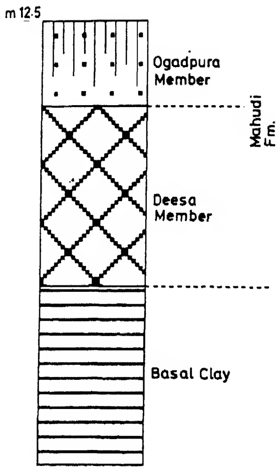


Sankesh Section

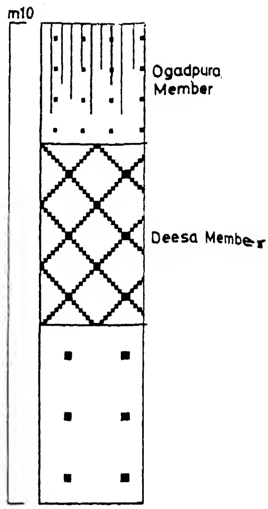
Khari River

Chanasma Section

Khari river at Chanasma has an exposed cliff of 12.5m where the clay horizon forms the base. Overlying it are the two members of Mahudi formation (7.5m).



Chansama Section

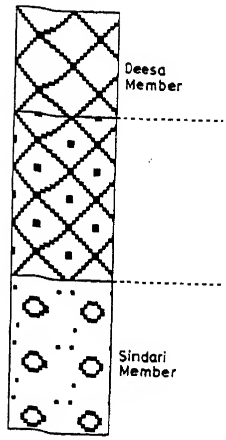


Patan Section

Saraswati River

Patan Section

The Saraswati river at Patan shows a cliff of 10m height, with only the upper parts (3.5m) of the Saroli formation. But the entire Mahudi formation (6.5m) is exposed.



Deesa Section

Banas River

Deesa Section

At Deesa, the gravels of Sindari member (6m) are exposed at the base over which lie the rubified silts of Hirpura formation (6m), which are in turn capped by the stabilised dunal sands of Deesa member provide a very good exposure. This section forms the type area for this member (4m) of the Mahudi formation.

Sindari Section

Luni River

Sindari Section

This section at Sindari located 45km south of Balotra provides the type area for the Sindari member of the lowermost Lakroda formation. In a cliff of 6m, gravels of this member (3m) are overlain by the dunal sands of Deesa member (3m).

Batala Section

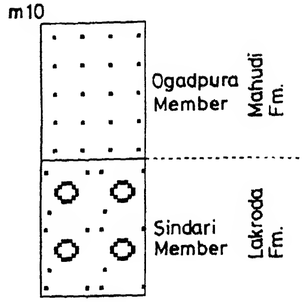
Batala located 9 km downstream of Sindari has a cliff of 10m. The base is made up of gravels of the Sindari member (5m) over which lie the dunal sands of Ogadpura member (5m).

Khundala Section

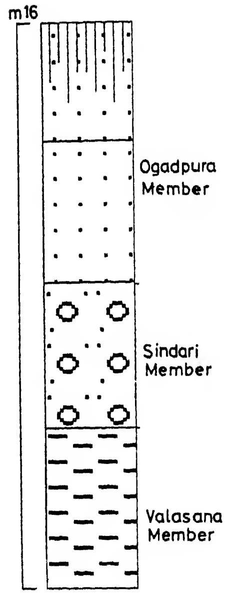
Khundala near Chitalwana has a 15m thick exposed sequence where the gravels of Sindari member (3.5m) comprise the most conspicuous feature, overlying the muds of Valasana member. A noteworthy feature of this section is that the overlying Deesa member (3.5m) exposed here shows a very conspicuous development of layered calcretes. Ogadpura member caps the top of the section. The present day shifting dunes of the Thar desert margin overlie this member.

Gurh Section

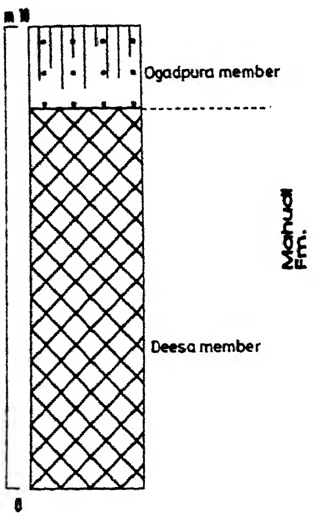
This locality 30km north of Chitalwana is conspicuous only for the continued pedogenetic changes in the Deesa member (7.7m) seen in the form of several more or less parallel calcrete layers. Ogadpura member (2m) provides the present day surface topography.



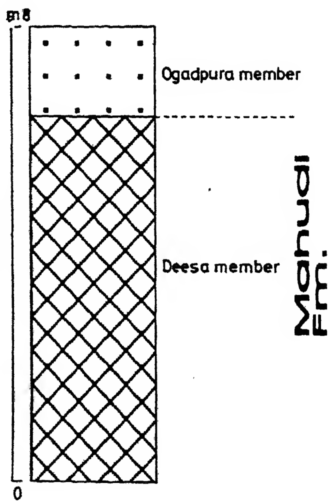
Batala Section



Khundala Section



Gurh Section



Chitalwana Section

Chitalwana Section

Chitalwana is 23 km NNW of Sanchor. A cliff of around 10m exposed here and all along downstreamward, consists of the aeolian silts and sands of Deesa member (8m) and the Ogadpura member (2m).

Depositional Environment

Studies of the representative samples belonging to different horizons of exposed successions from several localities have provided interesting petrographic details, diagnostic of the diverse processes of aggradation and degradation. The results provide an insight into the successions of depositional environments, sedimentary processes and post-depositional sub-aerial changes. These Quaternary deposits have been somewhat erroneously referred as the 'Older Alluvium' in the earlier literature. This nomenclature has rendered certain ambiguity in respect of the actual depositional environments prevailing at successive stages of their accumulation. Detailed lithological, textural and structural studies have however revealed a genetic model quite different from that envisaged by earlier workers. The non-marine Quaternary sequence not only provides an insight into the succession of geological events but it furnishes numerous evidence of prevalence of dominantly climate-related depositional conditions, fluvial as well as aeolian, with intervening periods of non-deposition and pedogenesis.

The lowermost exposed lithounit that is encountered in almost all the major river basins is a basal clay which could be representing a marine deposit and considering their bluish green to yellowish brown (10 Yr 414) colour conspicuous mottling and uninterrupted extension towards the sea, they appear to comprise tidal clays. The granulometric data of this horizon reveals that the main bulk consists of about 70-75% of clay fraction. The clay minerals in order of decreasing abundance are montmorillonite, chlorite and illite. Small percentages of kaolinite and vermiculite are also noticed. Chemically, the clays are found to be rich in SiO_2, Al_2O_3, and CaO. The high CaO content is attributed to the phenomenon of calcretisation. All these characteristics indicate that the bluish clay could have been deposited under marine conditions (sub-tidal) during the Middle Pleistocene high sea[39]. Subsequent to their deposition the clays were exposed to sub-aerial weathering processes, during which they underwent pedogenesis and calcretization. This is evidenced by the development of calcretic veins, strings and tubes. The fractures intersect to define subangular cohesive blocky aggregates. Concave upward curvi-planes are common in the unit. Striated surfaces (slickensides) are observed along such planes. Tubular forms of carbonate are remnants of root systems which form through a complex process of circum-root precipitation and subsequent infilling and are interpreted as rhizoliths[42,43]. Malik *et al.*[44], have identified these as vertisols.

Good cliffy sections of the sediments deposited over these marine clays are exposed on account of their subsequent incision by the present day rivers. The overlying gravelly and sandy horizons observed in the Narmada, Mahi and Sabarmati rivers point to their deposition in environmental sequences initially characterised by accumulation of fan deposits near the basin margin. The successive horizons of gravels point to occurrence of gravels at the base to begin with, marked by a debris flow an initial fan like accumulation which in subsequent periods, once

the basin was filled up changed over to inter-related environments like channel fills, flood plains, lateral migration of low sinuosity channels etc. Several parameters appear to have governed the deposition of sediments. Of these, an abrupt change in the regional physiographic setting is considered to be most important because it induces the unconfinement of the river along this boundary. Such an abrupt change in physiography was provided by a set of closely spaced step faults more or less parallel to the regional bounding faults (EMCBF, NGF) distinguishing the mountainous hinterland from the adjoining alluvial plains. In such cases instantaneous high surface run off responsible for aggradation consists of a high percentage of low order tributaries connected to the final order conduit, the feeder channel[45-47]

The various sedimentary facies identified in the three major river basins have provided a multistorey architecture of the deposits (Table V). Of course, the broad sequence and strata are comparable, but the lithofacies, when studied in

Table V Sedimentary facies exposed in the major river basins

FACIES	DESCRIPTION CODES	NARMADA RIVER	MAHI RIVER	SABARMATI RIVER	INTERPRETATION
Gms	Massive inversely graded cobbly to bouldery gravels	Present	–	Present	Debris - flow deposits
Gm	Matrix supported crudely stratified gravels		Present	Present	Channel bar deposits, as longitudinal bar deposits
Gt	Trough cross-stratified gravels	–	Present	Present	Minor channel fills by low sinuosity channel
Gsh	Gravel-sand couplets, crudely stratified	Present	-	–	Sheet flow deposits
Gp_1	Planar cross-stratified gravel	Present	Present	–	Longitudinal gravel
Gp_2	Planar cross-stratified gravel with lensoidal geometries	Present	–	–	Rechannelized flows genetically related to debris-flow events
Gp	Planar to epsilon cross-stratified gravel	–	Present	Present	Lateral accretion on the point bar
Gs	Sandy-gravel sheet lobes	–	Present	Present	Deposited at the channol margins
St	Trough cross-stratified gravel	Present	Present	–	Channel-fill elements of braided rivers
Shi	Horizontal to inclined stratified sand and silt assemblage	Present	Present	Present	Overbank deposits (under upper flow regimes)
Sm	Massive Sand sheets	Present	Present	Present	Sheet - flow deposits (buried by subsequent deposition after pedogenesis)
Fl	Fine sand and silt (interbeds)	–	Present	Present	Overbank waning flood deposits
Pc	Palaeosols, rhizoconcretions and calcrete nodules	–	Present	Present	Buried soils and precipitation of $CaCO_3$ solution along the cracks, channels

different rivers show considerable diversity in matters of details. Each river has its own story to tell and in each case, the response to the factors of tectonism and climate, in combination with the provenance and channel characteristics, had been distinct from the others. Each of the river basin in the proximal part close to the geomorphic divide is marked by a basal gravel accumulation. Downstreamward the sequences are better developed, and the lateral facies variations in all the river basins are quite marked from proximal to the distal end.

Overlying the fluvial deposits is a horizon characterized by 6m thick reddened (rubified) silts (5 YR 5\6). Since this formation does not show any clear cut stratification and is highly pedogenised, it is difficult to conclusively decipher whether the sediments are fluvial or aeolian in origin. It is fractured by multiple set of joints that has developed subangular blocky aggregates. The degree of carbonates varies greatly. The basal portion of the unit is characterised by a broad 0.5m zone profused with white calcareous nodules. The clay mineral assemblage is dominated by smectite with subordinate amount of illite and kaolinite. Hematite is also observed[44]. Pedogenesis is indicated by clay translocation along ped faces. The granulometric data supports their fluvial origin. The grains are bimodal, fine sands and silts, forming the main bulk of this formation; fall within the range of very well sorted to moderately well sorted (Av<0.352 to 0.51) and platykurtic (Av<0.67). The finely skewed trend is indicative of the fact that the sediments were derived from one single source. The standard deviation illustrates the fact that the sediments are intermediately matured and fall within the moderately well sorted regimes. The plots of skewness against standard deviation fall within the riverine environment thereby suggesting that the sediments were laid under fluviatile environment. The red colouration has been found due to the presence of finely derived ferric oxides. As this rubified silt horizon occurs all over the Mainland Gujarat and is very well exposed, especially in Mahi and Sabarmati, it provides an excellent and dependable marker horizon.

The rubified silts are overlain by a thickness of structureless, porous and calcareous silts showing conspicuous pedogenisation and calcretisation. This formation consists of stabilized sands and silts and typically exhibits a dunal topography. It occurs all over Central and North Gujarat and extends from Narmada river in the south to as far as Luni in the north. Granulometric analysis has revealed the particles to comprise mostly silts and fine sands. The coarse silts are the most dominant and form 40-60 % of the total grain size bulk. The sediments shows a poor to very poor sorting (Av 1.0 to 0.3) and leptokurtic to very leptokurtic nature (Av 1.11 to 2.1). These characteristics considered together with the structurelessness, porous and homogenized thickness typically suggest an aeolian origin. In fact, this horizon over which a brown forest type of soil has developed has been referred by most earlier workers as loess like, having been deposited during the Terminal Pleistocene aridity. No doubt, these aeolian silts show considerable resemblance to the typical loess and its section stand out as vertical

bluffs in the Sabarmati and Mahi river basins. Studies under microscope have shown that the constituent grains are of quartz and feldspars, and the mass is totally devoid of any layering or lamination. Nowhere in western India this horizon shows any layering either based on size or mineralogy and this feature is characteristic of their having been deposited by aeolian processes. These are stabilized as is evidenced by soil formation over them. The topmost portion of the sequence is made up of fine more or less unconsolidated sands that overlie the stabilised aeolian silt horizon. To the north-west of the river Luni the area is studded with numerous shifting dunes of fine sand forming the Recent accumulation of the present day Thar desert environment.

Basinwise Lithofacies Description

Narmada River Basin

The deposits point towards the existence of an alluvial fan environment, indicating an abrupt change in the regional physiographic setting where the river becomes unconfined; the abrupt change characterized by faults related to the Narmada Geofracture, that separated the mountainous hinterland from the alluvial plains to the northwest and west[30] (Fig. 25). The rapid high surface run-off responsible

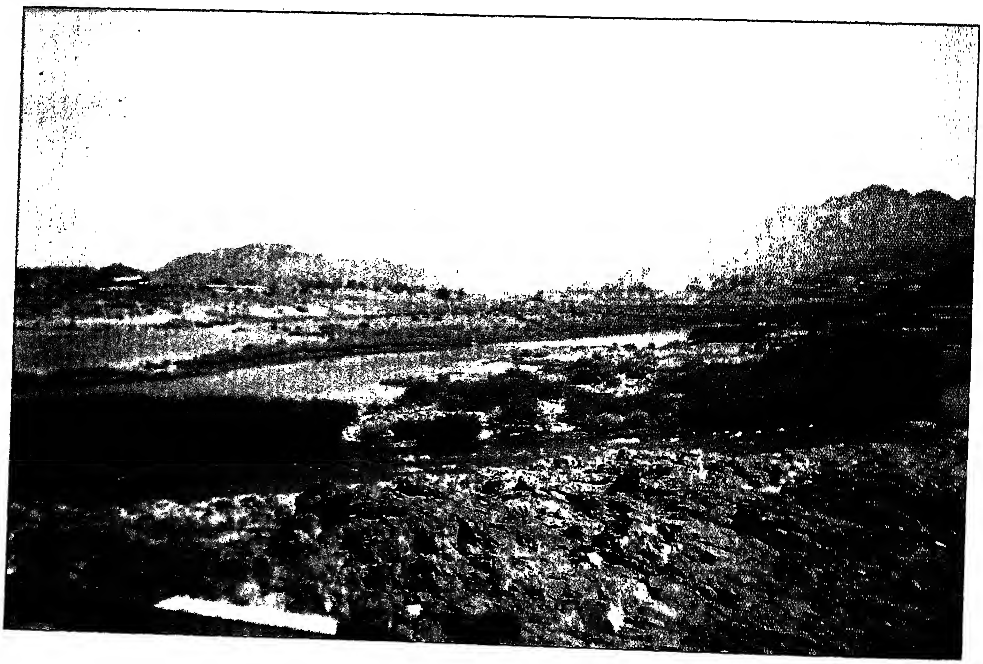


Fig.25 Mountainous hinterland at Navagam upstream view of Narmada looking SE

for fan aggradation occurred through a high percentage of low order tributaries connected by the feeder channel of the fan. The mechanism of deposition and processes were more or less identical to those invoked by a number of workers in identical geological settings elsewhere[45,46,48-59].

The main bulk of the thickness consists of deposits built by debris flows and sheet flows. Interestingly, unlike Mahi and Sabarmati, in Narmada, successive aggradational phases cannot be clearly demarcated: Of course, their existence has not been ruled out and in the Narmada alluvial sequence in totality, especially in the sediments downstream, evidence of non-deposition and pedogenitic changes have been reported[8]. The deposits comprise the following five lithofacies and whose varying dominance at each site (Fig. 26) contributes towards the multistorey architecture of the fan[30].

(1)	Gravel-sheet facies	Gms
(2)	Gravel/sand-couplet facies	Gsh
(3)	Sand-sheet facies	Sm
(4a)	Large-scale planar cross-stratified gravel facies	Gp_1
(4b)	Small-scale planar cross-stratified gravel facies	Gp_2
(5)	Trough cross-stratified sand facies	St

Facies Description

Gravel Sheet Facies - (Gms) – The facies consists of laterally persistent matrix-supported gravels and is observed at all localities in varying proportions. The gravels are inversely graded, poorly sorted and essentially polymodal in nature (Fig. 27 and 28). Typically 25-35% sand mud matrix is present. The larger clasts are restricted to the upper margin of each unit. The upper and lower bounding surfaces are gently convex upward and non-erosive. However, the upper bounding surfaces show greater convexity imparting the unit a convex lens morphology in cross-section. The gravel unit occurs as solitary sheets and also as composite units built upon vertically stacked sheets. The sheets vary in thickness from 0.5m to 2m. The clasts are discoidal, cuboidal, tabular and spheroidal. Wherever there is predominance of discoidal clasts, a crude imbrication in the upstream direction (SE) is observed implying northwest directed palaeocurrents.

The clasts show a high degree of rounding. The maximum clast size decreases in a systematic manner towards northwest from 150 to 10cm. Another feature illustrated by the gravel-sheets is the clustering of clasts in groups of three to five. Similar organization of clasts in conglomerates has been described as nesting of clasts[60]. The basal gravels in all sections is strongly cemented by calcium carbonate[61]. The inverse grading of clasts along with large clast size and protrusion of clasts at the upper bounding surface of each unit suggests that the facies represent viscous debris-flows[30]. Similar facies have been reported extensively from alluvial

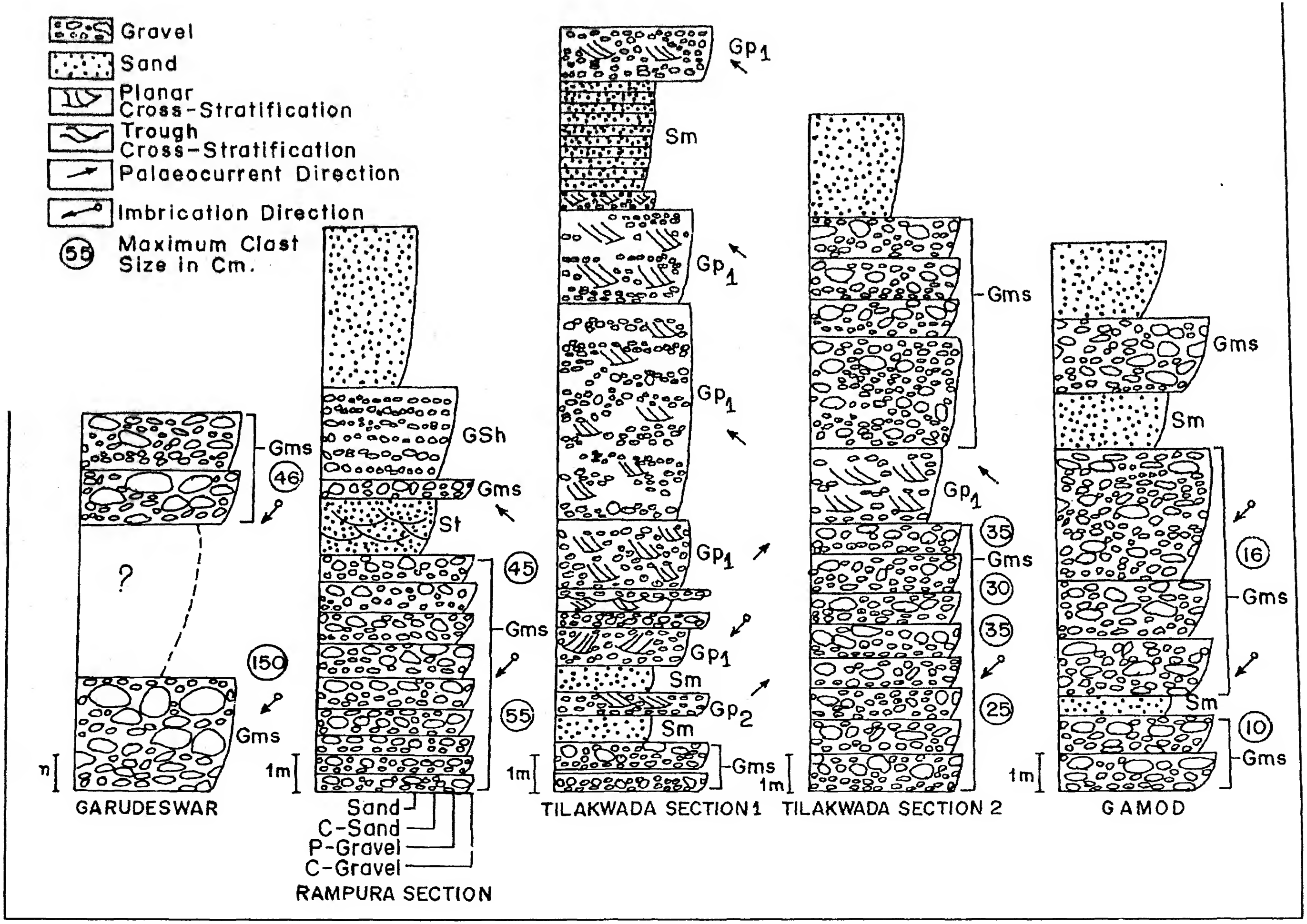


Fig.26 Lithologs measured at various sites showing palaeocurrnt and imbrication directions (5-10 counts per level), maximum clast size and stratification types[30]

Fig.27 Right bank cliff at Tilakwada exhibiting inversely graded Gms facies

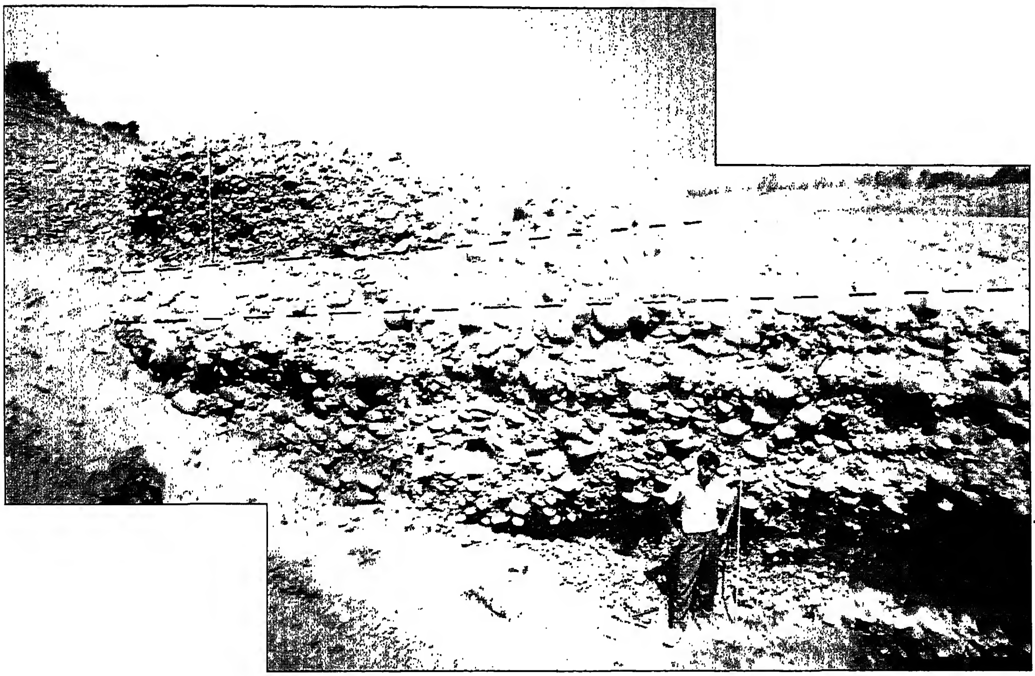


Fig.28 Inversely graded Gms facies at Rampura

fan deposits[50,54-57,59]. The main mechanisms involved for large clast entrainment were a combination of dispersive pressure and buoyancy[62]. This is reflected in the segregation of the larger clasts within each unit away from the lower bounding surface, a feature also recognized by Hubert and Filipov[63]. High clay content of 3% and clast size governed the mobility of the debris-flows, the former providing cohesive strength (by reducing permeability and increasing pore pressure) and the latter determining the structural framework[62]. Clustering of clasts in nests of upto five, might either indicate an accumulation due to an obstruction by a leading larger clast[46] or a tendency for clasts to migrate towards region of least internal shear[60].

Gravel/Sand-Couplet Facies (GSh)—The facies consists of gravel-sand couplets of 10cm-15cm thickness. The couplets are horizontally stratified. The sand component of each couplet overlies the coarser fraction. The clasts are pebbles and cobbles of spheroidal, discoidal and cuboidal basalts, are subrounded and do not show any distinct imbrication. In the sand fraction, pebbles decrease in content and cobbles are totally absent. The sands are discontinuous in some cases, and their individual ribbons bifurcate laterally. The gravels are unsorted, polymodal with no internal stratification. The gravel-sand units occur as vertically stacked cycles numbering upto seven. The suite of characters shown by this facies suggest that the gravel sand couplets resulted through sheet-flow processes. The late stage deposition of sand subsequent to gravel deposition implies a suspension fall-out mechanism, responsible for the origin of the sand component of each couplet. The couplets also suggest low turbulence in the flows which enabled the step-wise deposition of gravel and sand with incremental fall in the capacity of the flow. Similar couplets have been described by Blair and McPherson[45], who interpret the couplets as due to flow hydraulics, initiated by flow expansion and decrease in slope gradient. Equivalent controls seem to have been responsible for the genesis of the couplets in the present case.

Sand-Sheet Facies (Sm)—Laterally continuous, internally unstratified sheets of sand comprise this facies. The units are usually 0.5m thick and bounded by planar non-erosive surfaces. Associated with the sheets are occasional stringers of pebbly gravel. The facies also occurs as sand lenses in the massive gravel deposits (Gms) (Fig. 29). The sand-sheets point to sheet-flood events of low turbulence which led to the separation of the suspended sand-load and its deposition further down the lobe. Deposition resulted owing to reduction in flood velocity of the unchannelized flow[51]. The association of Gp2 facies with sand-sheets point to the prevalence of confined flows subsequent to the deposition of the sand-sheets.

Planar Cross-Stratified Gravel Facies (Gp)—The cross-stratified gravel facies occur at two scales. At the smaller scale it contributes to the fan architecture as lenses

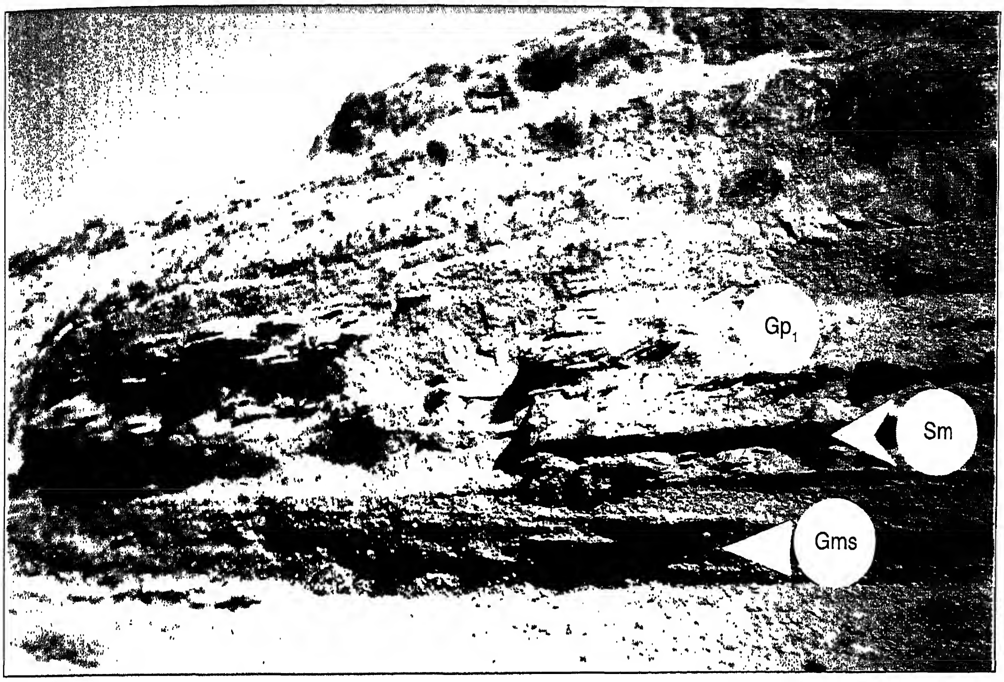


Fig.29 Unstratified sand-sheet and Sm facies at Tilakwada

while at the larger scale, it occurs as pervasive, laterally continuous gravel ribbons (Fig. 29). These two sub-facies have different origins and are described separately.

Large-Scale Planar Cross-Stratified Gravel Facies-Gp1—The facies (Fig. 16) is bounded by sub-horizontal planar surfaces. However locally these surfaces may also be erosive (undulatory). The gravel units are commonly 1.5m in thickness, with no significant change laterally even upto a distance of 50m. The foresets dip consistently at an high average angle of 30° and have concave-upward surfaces. Within each foreset cycle the clasts are normally graded. The planar cross-stratified beds occur as cosets as well as solitary units. The clasts which are granules and pebbles of basalt are moderately rounded. At the basal surfaces, (lag) pebbles and cobbles are observed in each set. The cross-stratified gravels are a result of the downstream migration of mid channel bedforms. The facies represents the downstream accretion element (DA) of Miall[64]. The high-angle dipping foresets are the result of avalanching slip-faces at the leading edge of the gravel bar[65]. The clasts size indicates a derivation through surface winnowing of the debris-flow units (Gms) by overland channelized flows. Identical facies have been attributed to deposition on longitudinal gravel bars[54].

Small-Scale Planar Cross-Stratified Gravel Facies-Gp2—These pebbly clast-supported gravels are characterised by their lensoidal geometry. The lenses are distributed as solitary units within the ubiquitous Gms facies. They are usually less than 0.5m in thickness and show an average foreset dip of 25°. At some sites these gravels are more sandy and occur in close association with sand-sheet facies. The intimate association of the small-scale clast supported gravels with Gms and Sm facies suggest genetic link between them. These gravel bedforms were formed immediately after a debris-flow event, a period during which the gravel bed-load flows were rechannelized as small streams.

Trough Cross-Stratified Sand Facies-(St)—The trough cross-stratified sand facies was observed at only one site. The unit is ~2m thick. The normally graded foresets are large concave upwards and tangential, dipping at an average angle of 25° (towards the north. At the base, the unit begins with small-scale sandy bedforms which are draped over the underlying cobbly clasts. The trough cross-stratified facies represent the channel fill elements of rivers[53] which dominated the fan surface during intervening quiet periods between successive episodes of fan aggradation. They are comparable with Gp_2 facies in their mode and time of formation.

At the sites studied, the abundance of each facies type varies. However, the Gms facies dominates the alluvial architecture as can be clearly seen from Fig. 30 and Table VI. The alluvial architecture was constructed by both confined and unconfined flows. Of the primary depositional processes that directly contributed to the agggradation of the fan, viscous debris-flows played a major role, with a minor contribution by sheet-floods. Debris flow deposits (Gms facies) make up over 70% of the alluvial architecture. In this aspect the Narmada alluvial fan may be classified as type 1 fan[45-46]. Debris-flows aggraded the fan at both proximal and distal ends. The maximum clast size decreases down-fan in agreement with the expected fall in flood velocity. Evidence of intervening quiescent periods between fan aggradation events is present in the form of large- scale planar cross-stratified gravel (Gp_1) and trough cross-stratified sand (St) facies. Braided rivers with longitudinal bars dominated the surface of the fan during these phases.

A major deviation from the norm is observed in the clast roundness of the debris-flow deposits. Most of the alluvial-fan deposits are recognised by their angular to subangular nature[48-50,52-54,59,63]. Angularity of the clasts has been stressed by Blair and McPherson[45], and the only exception they accommodate is a conglomeratic provenance. In tropical alluvial fan settings, however sphericity is also attained by initial spheroidal weathering and subsequent abrasive rounding on river beds[55]. Fans formed under these conditions are as a rule dominated by stream-flow processes and abundant organic detritus. Both are absent in the Narmada fan deposits, which coupled with calcretization (case hardening) indicates that the deposits were formed under semi-arid conditions. Chamyal *et al.*[30] invoked the greatly

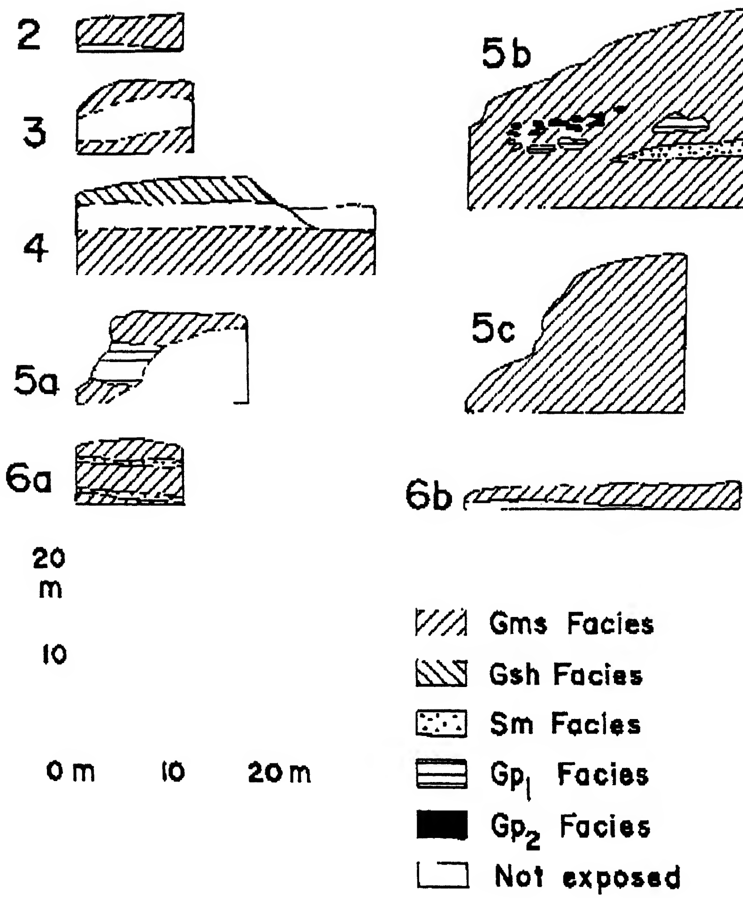


Fig.30 Schematic cross-sections of exposures showing the relative dominance of facies. Note that the Gms facies dominates (>60%) the alluvial architecture of all sites

***Table VI** Exposure summary; a-Linear distance, b-length x height, c-Primary depositional characteristics in 40% of area destroyed by erosion*

Site no.	Distance from apex (km)[a]	Area of exposure (m²)[b]	Facies Percentage Gms %	Sm %	Gsh %	Gpl %	Gp2 %	St %
2	26	125	100					
3	7.0	130	100[c]					
4	12.7	512	68		25		—	7
5a	16.5	174	64			36		
5b	16.5	829	91	4.5		1.5	3	—
5c	16.5	422	100					
6a	23.0	128	89	11				
6b	23.0	136	100					

elongated catchment area upstream of the fan apex as a determinant. Rounding of clasts took place when the angular fragments were transported as bed load along the lengthy course of the Narmada (feeder channel), to be temporarily arrested as channel bars upstream of the fan apex. Hemispheroidal and discoidal clasts also attest to such a mechanism. The flat base suggests that these clasts rested on a stream bed while the exposed surfaces of the clasts were modified to their present shapes by the stream flow. These subrounded clasts were then eroded from the bars, remobilized and entrained in viscous debris-flows during flash floods.

Mahi River Basin

The sediments in Mahi river basin were deposited by braided river distributary system. As the river flows across the quartzitic terrain the sediment clasts available were mainly of gravel and sand size. No debris-flow deposits are noticed in the upper reaches. Overall deposition in the Mahi river basin has taken place in numerous inter-related environments like braided river, flood plain on the channel margins, channel fills, lateral migration of channels and low sinuosity of the channel etc., which gave rise to accumulation and development of both fining as well as coarsening upward sequences.

From the palaeocurrent data and the sedimentary structures, it is observed that the present day Mahi has incised older deposits now seen in the form of high cliffy banks all along its course; cliffs range in height between 20-35m. The incised succession comprises assemblages of various lithofacies and reveals numerous sedimentary structures noticed in the selected vertical lithounits (Fig. 31). The lithofacies encountered are as under:

(1) Matrix supported gravel	Gm
(2) Trough cross-stratified gravels	Gt
(3) Planar cross-stratified gravel	Gp
(4) Sandy-gravel sheets	Gs
(5) Interbed of sand and silts	Fl
(6) Horizontal to inclined stratified sand and silts	Shi
(7) Massive silts	Sim
(8) Palaeosols, calcrete layers and rhizocretions	Pc

Facies Description

Matrix Supported Gravel-(Gm)—Gm facies are well exposed at Kadana and rest over the quartzites. This 30m thick lithounit reveals coarsening upward cross-stratified gravel, and the facies comprises poorly sorted, sub-rounded to rounded quartzitic gravelly and pebbly clasts. Larger clasts ranging in size from 4 to 9cm are seen

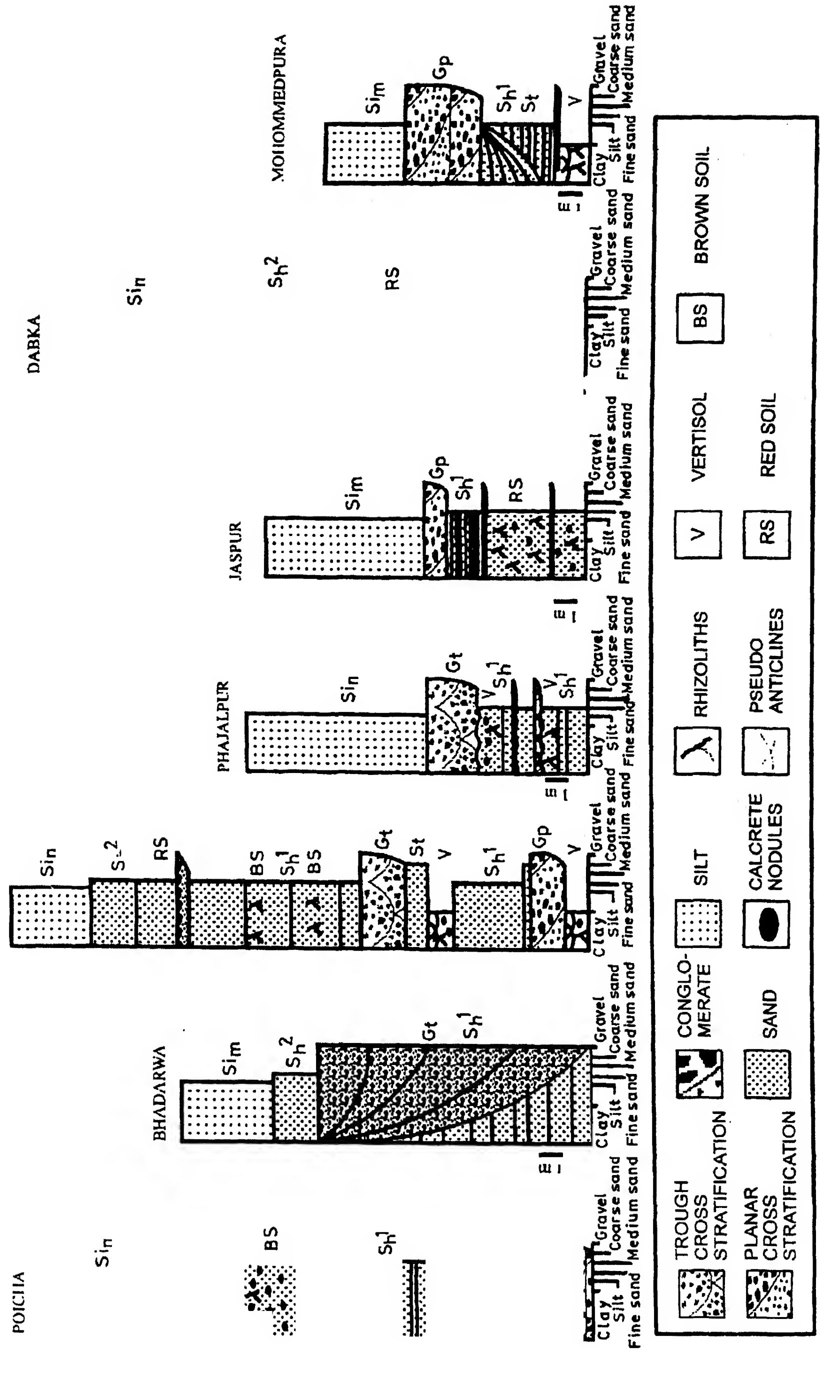


Fig.31 Lithologs of various sections showing facies types[44]

embedded with the interlayering of bedding plains. Bedding thickness varies from 2.5 to 15cm and shows coarsening upward gradation. Such cycles are about 7 to 8 and are separated by the imparting bedding planes, but the boundary between each plain is not so distinct. The matrix is coarse to medium grained sand with subordinate amount of silt and clay. The accumulation of cross-stratified gravel was associated with major mid-channel bar. The coarsening upward nature of the sequence is attributed to gradual rejuvenation with intervals of temporary abandonments in the braided complex[66].

Trough Cross-Stratified Gravel Lithofacies-(Gt)—The Gt facies are abundant in the succession in the form of sediment bodies ranging between 0.5 to 3.5m thick (Fig. 32). It occurs both as lenses as well as laterally persistent sheets of irregular thicknesses. The facies shows an erosinal contact with the underlying Fl-facies (Fig. 33). The gravel lithofacies is characterised by well developed trough foresets with shallow concave upward bounding surfaces, with a dip of about 100-160 which upward become planar to horizontal. The facies at places shows planar foresets which were eroded by later phases of fluvial activity, marked by a tangential relationship between planar and trough beds. The stratified Gt-facies shows typical fining upward interbeds of coarse and fine packages. The coarser beds are of 12 to 15cm in thickness, and shows clustering along the beds, while the fines (coarse sand) are of 6 to 8cm. The clast-size ranges from 1 to 1.5cm comprising mainly of basalts, they are sub-rounded to rounded. The larger clasts showing clustering are mainly of carbonates (eroded calcrete crusts) whose size ranges between 2 to 2.5cm. The facies at places shows some embedded aggregate clasts of pedogenised mud also; the size of mud clasts ranges from 15cm to >50cm. The matrix mainly consists of fine sand.

The trough forsets show better development where the lithounit has attained its maximum thickness. The palaeocurrent direction is SE to SSE, with a depositional angle of about 10°-16° due east. This lithofacies is the product of sedimentation of a high flow regime, with maximum discharge of sediment supply. The erosive nature of the contacts are indicative of high energy conditions as well as represent lateral migration of bars with curved shallow channel scours or by minor shallow channel fills[64,67]. The trough axes of the forsets are taken as the channel orientation with high angle values of plane beds and these suggest that they must have been deposited under bar morphology due to increase in channel gradient or were deposited by low sinuous channel under high energy flow[68]. From the lithology as it comprises mainly carbonate nodules, high shear stress are needed to erode a compact carbonate horizon formed in alluvial plains in its upper reaches. Such sudden change in flow regime and sedimentation pattern can be attributed to tectonism.

The concave upward base of trough beds, which shows vertical as well as lateral accretion are typical deposits of low-sinuosity channel morphology[69-71].

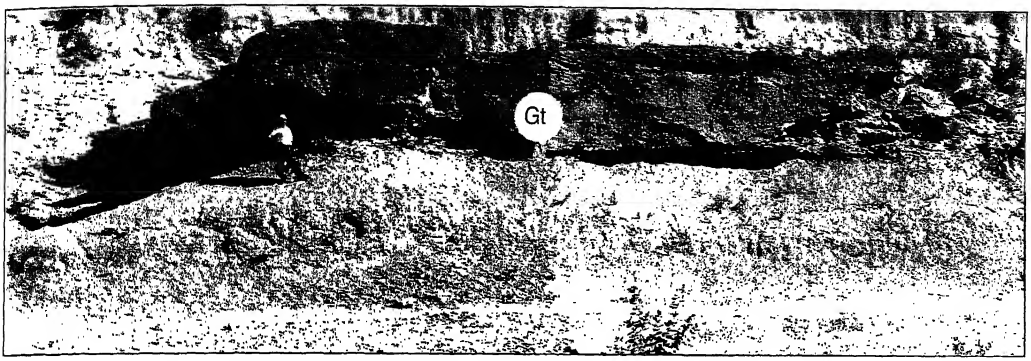


Fig.32 Trough cross-stratified gravel facies at Rayka

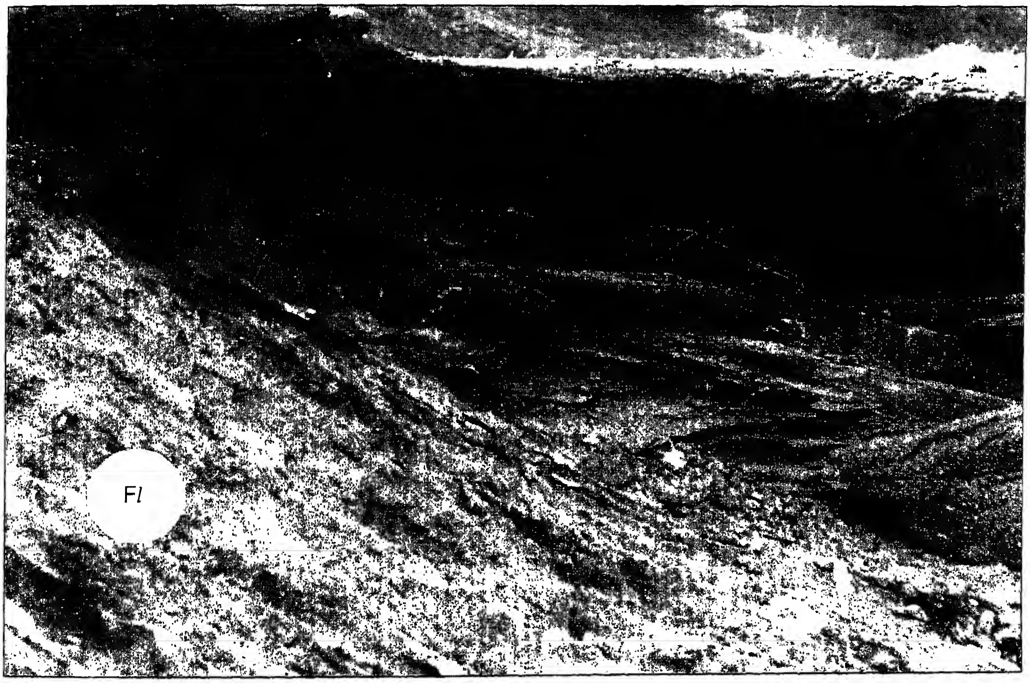


Fig.33 Trough cross-stratified gravel (Gt facies) overlying the Fl facies at Rayka

Planar Cross-Stratified Gravel-(Gp)—Gp facies is well exposed in the lower reaches of the Mahi basin (Fig. 34), around Bhadarwa, Dodka, Rayka and Vasad. This facies overlies the pedogenised mottled clays and is usually 4-5m thick occurring as solitary sets and cosets. The gravel clasts comprise mainly of calcrete nodules and basaltic fragments. The size of the clasts ranges between 15 and 20mm in

Fig.34 Close-up view of planar cross-stratified gravel Gp facies at Rayka.

diameter; they are well sorted and well rounded in shape. The matrix is dominated by fine sand, silts and clay. The gravel lithounit shows planar cross-stratification. The parting planes of the stratification are marked by the lenses of clay laminae occurring parallel to the bedding planes.

The bounding surface between the underlying pedogenised mud is sharp and at places shows undulatory erosional contact. The foresets of the cross-stratified horizon dip at an angle of 15°-18° due SW. At places the shape of the laminae changes from tangential to concave upward and show decrease in the foresets dip angle. The topsets also show variation in the dip angle from very low to horizontal. The thickness of the Gp lithofacies varies within a distance of 1 to 2km, downstream from Rayka and almost merges with gravel-II (Gt) near Vasad. The absence of Fl facies and presence of vertisol horizon, suggests that the deposition of Fl-facies and vertisol horizons were deposited in an undulatory palaeotopography. The erosive nature of the contact marks shallow channel geometry of 2 to 2.5m deep. The change in the dip angles of foresets suggests fluctuation in flow regime from low to high[72-73]. The variation of the dip angle of the topsets marks the upper portion of the bar that were formed during the lateral migration of the channel. The varying thickness of Gp-lithofacies suggests that the gravel was depo-sited in the deepest part of the channel in the form of longitudinal cross-beds on the point bars of a meandering channel under upper flow regime[64,74-76].

From the palaeocurrent data and the sedimentary structures it is evident that the channel was of meandering nature that gave rise to the development of planar to epsilon cross-beds due to lateral accretion in the SW direction, having a flow due SE. Such type of sediment load deposition generally takes place during waning peak flooding conditions[77]

Sandy Gravel Sheet Facies-(Gs)—It is well exposed in the upstream direction of the present day Mahi around Rayka. The gravelly sand occurs as a sheet like body. It mainly consists of carbonate and basaltic clasts. The grain size tends to become increasingly fine, as coarse sand merges with the silts and clay assemblages. The Gs-facies occur in association with the Gt-facies, but is more calcretized than the Gt-lithofacies. The gravelly sand sheet pinches out and merges into the fine sand, silt and clay sediments assemblages. This phenomenon marks the margin of the shallow palaeo-Mahi channel around Rayka and Dodka. The Gs-facies confirms its deposition over the channel margins. The greater compaction of Gs-facies suggests that during the shifting of the channel this portion was exposed to weathering and chemical precipitation prior to that of the Gt-lithofacies.

Overbank Accretion Facies-(Fl)—This lithofacies occurs over the Gp-facies, owe their sedimentation by overbank deposition due to gradual vertical aggradation of sediments from suspension following the flooding events, giving rise to alternate layers of sand-silt and clay[74,79]. The contact between Fl and Gp facies is slightly undulatory and at places shows erosional contact (Fig. 34). The overall facies thickness varies from 3 to 4m. Horizons of this facies can be traced laterally in downstream direction of the Mahi between Poicha and Angadh, then they split into a thinner units of sand. The marly band (calcrete bands ?) are marked which conforms with the lithological boundaries, are indicative of fluctuating groundwater levels related to the waning flood conditions. After this there was deposition of very fine silt horizon of about 0.5 to 0.75m overlying the Fl-facies. This very fine silt horizon marks an end of the first flood event and last phase of receding flood water.

As the Fl-facies does not show any well developed pedogenic feature, it is concluded that the surface must not have been remained exposed for longer period to sub-aerial weathering and the vegetal growth was very sparse, which is well marked by less concentration of (about 3%) buried rootlets. It is overlain by a pedogenised mud horizon; thickness of which is not uniform and is suggestive of an uneven topography over which the deposition of fine clay sediments had taken place. It is very much similar to the pedogenised mud horizon that underlies the Gp-facies. It shows dark brown 10YR 4/2 colour. The thickness varies from 1-1.5m., shows desiccation cracks along which the drab haloes are seen to have formed. These drabs mainly comprise leached carbonate material and show distinct greenish colour. The leaching must have taken place along the rhizolithic cracks. This mud horizon shows homogeneous sediment size (mainly clay) and is marked by mottling, cracking and pedoturbation, hence can be classified as a vertisol[79]. It seems that the deposition of this facies had been taking place over a flat to slightly scoured erosional surface of the underlying gravelly facies. Such type of unevenness of the sediments is indicative of the margins of a huge longitudinal bar system. The very fine silty horizon marks an end of the Ist flood event and the last phase of the receding flood water.

Horizontal to Inclined Sand Facies-(Shi)—This lithofacies occurs between the overlying facies Gt and underlying Pc (Vertisol-II) horizon. It comprises a fine grained sand and silt horizon. The sand and silt packages show stratification, present as thick as 15cm and as thin as 10cm plane-beds. The beds at places shows inclination of about 10°-15°. This lithofacies is the product of overbank deposition under an upper flow regime during waning flood episode on plane bed conditions[80-87]

Massive Silts (Sim)—This facies occurs extensively in the Mahi river basin (Fig. 35). Ranging in thickness from 2-7m, it contrasts with the irregular outcrop expression of the other facies and forms steep vertical bluffs. The facies is massive, structureless, yellowish brown in colour and is studded with centimeter size carbonate nodules. The facies shows identical grain size distribution with mean grain size ranging between 3.8 to 3.85, are well to moderately well sorted and contain an average of 58 to 64 % of silts. Based on all these characteristics this facies is interpreted having formed through aeolian agencies[44]

Palaeosols, Calcrete Layers and Rhizocretion Facies-(Pc)—The exposed alluvial succession shows three distinct horizon of buried soils occurring above the Gt facies. These owe their origin under overbank deposition. These palaeosols are well exposed

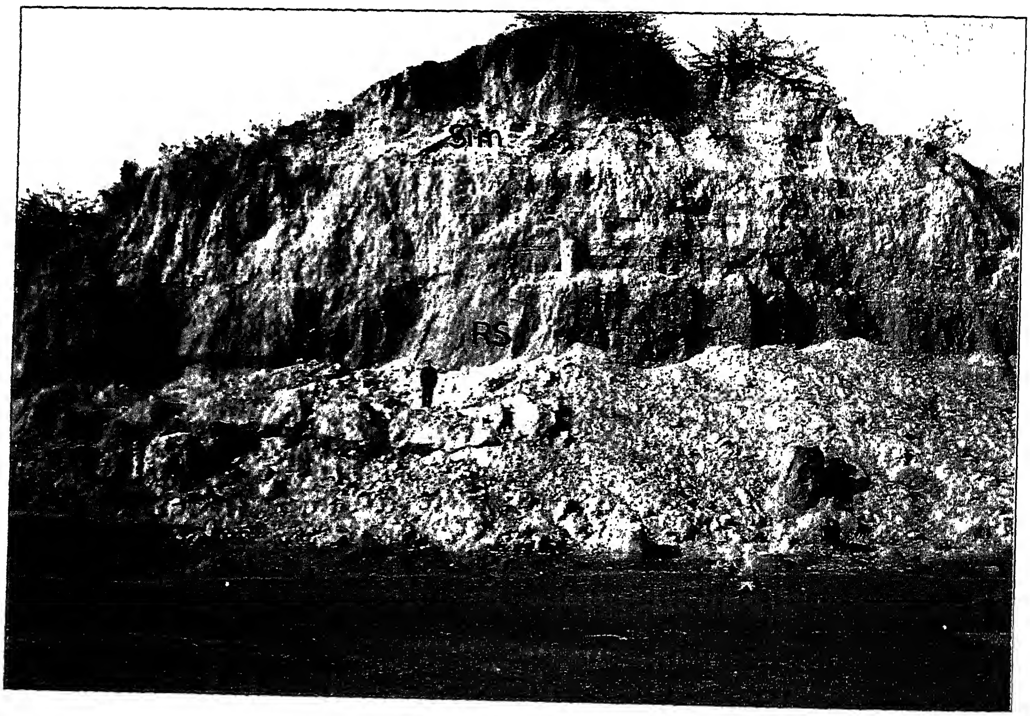


Fig.35 Left bank cliff view of rubified silts at Dabka

at Rayka, mark successive individual aggradational surfaces, which remained exposed to sub-aerial weathering and buried by subsequent episodic flood events. From the chroma and appearance based on field identification, each of these soils shows variation in the colour. Palaeosol-I show 10YR 5/4 yellowish brown colour, which overlies the Gt-facies and is separated by 1m thick Fl-facies. Palaeosol-II show 10YR 7/4 very pale brown, while the palaeosol-III shows 5YR 5/6 yellowish red colour. The variation of the soil colour could be due to temporal differences of lithological and climatic factors during the various depositional events and the post-depositional diagenetic changes.

The thickness of individual palaeosols varies and at some places they are weakly pedogenised. This suggests uneven flood plain topography, according to Smith[88] the flood plains will not have uniform sedimentary environment and are marked by variation in topography, the burial at particular site will depend on the time interval between each overbank flood events and on the net sediment accumulation. These palaeosols do not show any well developed 'O' and 'A' organic bearing horizons. It appears that these horizons may have been eroded during the depositional episode that followed, or during the period of non-deposition. The grain size data of these palaeosols shows average mean grain size ranging between 3.5 to 4 phi, moderate sorting, platykurtic and coarse to strongly coarsed skewed nature. The red (rubified) soil (Fig. 35) occurs as marker horizon to this late Quaternary sediment succession. The pedogenised soils form a part of sandy loam in which the clay percentage is very low ranging between 18. 56 to 11. 13%. No colour variation is seen in the red soil, while the A-horizon is also absent, only the Bk horizon marked by accumulation of carbonate nodules (calcrete) and show high percentage of illuviated clay. As this soil shows high percentage of smectite/montmorillonite, it suggests the source area to be the basaltic and granitic terrain, which must have provided the Fe and Mg rich minerals. The ferromagnesium minerals when deposited under prevailing humid condition might have undergone hydrolysis and released the iron compounds: the following dry climate caused the dehydration of these iron elements, giving thereby a reddish colour to soil[89]. The uniformity in red soil profile indicates that the formation of iron compound were homogeneously distributed throughout. Such processes are attributed to rubification[90].

The diverse lithofacies point towards three phases of aggradation. The aggradation phase 1 covers stratigraphically, deposits upto the second gravel horizon at Rayka marked by Gt, Gp, Shi, and Fl lithofacies. The alluvial aggradation was in a braded channel environment. The presence of vertisols on overbank facies suggests that bank cohesion was high. The coarser bed load was dominated by calcrete. The sinuous crested sediment load was derived by erosion of upstream banks. Such bank erosion was possible during flash floods, commonly recorded in arid zone rivers[86]. During the second aggradational phase, the river mainly transported sand and silt. Cross-stratified calcrete gravelly horizons (Gt) are few

and suggest presence of occasional small scale channels. A high degree of ephemerality and transport of sediment as suspension load, followed by calcification of the river bed sediments during the succeeding drier periods were responsible for the deposition of alluvial sediments of this phase. The river channels were shallow with a high width to height ratio. The overall facies characteristics point to sheet flooding to be the possible mechanism of aggradation. The third aggradational phase was dominated by the deposition of homogeneous massive silts (Sim). The landscape was covered with aeolian dunes which show characters similar to the classical loess sequences. The absence of soil illuviation horizons are related to shorter durations of stabilization events.

Sabarmati River Basin

The Sabarmati river basin reflects an alluvial fan environment quite similar to that of the Narmada. The various horizons exposed in the river valley with their characteristic features point to a deposition in, a combination of fluvial and aeolian environments. The oldest exposed Quaternary horizon in the study area is the basal bluish clay, correlatable with the comparable formations in Mahi and Narmada. This horizon comprises 70-75 % of clay and is rich in illite, chlorite and montmorillonite. Subsequent to their deposition, these were exposed to subaerial weathering processes, during which they underwent pedogenisation. This is evidenced by the development of calcrete veins, strings and tubes. The high CaO content is also attributed to this phenomena. The lithofacies encountered in the area are as under :

(1) Matrix supported gravel	Gms
(2) Planar cross-stratified gravel	Gp
(3) Trough cross-stratified gravel	Gt
(4) Sandy-gravel sheets	Gs
(5) Interbeds of sand and silt	Fl
(6) Planar cross-stratified sand facies	Sp
(7) Palaeosols, calcrete layers	Pc

Facies Description

Matrix Supported Gravel-(Gms)—The overall geomorphic setting of this gravel facies marks the onset of fluvial sedimentation. The oldest exposed gravel is seen to comprise clastic grains showing a size variation ranging from cobbles to fine sand; at many places, the gravels tend to be clast supported, whereas at other places, the coarser clastics are embedded within a matrix of finer particles which may or may not show cementation. In case of cementation, either it is calcite or ferruginous

matter. The gravels are crudely stratified and show both normal and inverse graded bedding. In hand specimens the clasts are found to be mostly of quartzite with some granite. Thin section studies of the finer clastics (matrix) reveals quartz and microcline feldspar. The quartz grains are of two varieties—rounded to sub-rounded and angular to sub-angular. The feldspar is almost invariably subangular. The cementing agency is calcite. The depositional direction was southwesterly. As the mean direction of the longest axes of the gravels is also NE-SW, the original flow direction was oblique to the present day river flow.

The gravel characteristics point to their formation by the process of a low viscosity debris flow[47,58,91,92]. The range of phi and the inclusive graphic standard deviations fall very well within the one suggested by Bull[91], according to whom the phi deviation for the mud (debris) flow deposits ranges from 4.1 to 6.2 for semi-arid alluvial fans. That the gravels originated mainly by a combination of debris and muddy stream flows is evidenced by the fact that they fulfil the various criteria postulated by Ballance[49], Bull[47,91], Hooke[93], McArthur[58] and Pierson[59] for invoking a debris flow deposition. According to Pierson[59] such deposits are formed during flood events in a humid climate when the gravelly channel oscillates between a very muddy stream flow to a debris flow. Fractured mud horizon which overlies this gravel indicates that the energy conditions of the depositing streams progressively weakened and finally the deposition stopped and exposed to weathering. The pedogenisation of this mud points to the period of non-deposition before the onset of the next fluvial cycle.

Planar Cross-Stratified Gravel-(Gp)—The overlying gravel which marks the beginning of the second fluvial cycle is separated from the underlying gravel by a pedogenised mud horizon and the Gp facies shows a sharp contact at places with the Gms facies. It is typically characterised by cross-stratification and numerous interbeds of finer gravel and coarse sand which shows normal as well as inverse graded bedding. The gravel lithounit shows planar cross-stratification. The parting plane of the stratification are marked by the lenses of clayey laminae occurring parallel to the bedding planes. The bounding surface between the underlying pedogenised mud is sharp and at places shows undulatory erosional contact. The foresets of the cross-stratified horizon dip at an angle of 10° to 12° due SW. At places the shape of the laminae changes from tangential to concave upward and show decrease in the foresets dip angle. The nature of this gravel is quite different from the underlying one. Though it shows presence of clasts with a wide range of variation from cobbles to coarse sand, the main bulk of coarser fragments is of pebble size, large size fragments being scarce. Significantly this gravel bed is highly compact, almost rock like and could very well be termed a conglomerate. The coarser clastics are embedded in finer matrix and at places are cemented by calcium carbonate. The pebbles are of mostly quartzite with a conspicuous proportion of granite calc-silicate, feldspar (microcline and perthite), agate, jasper and chert.

The calcareous cement is indicative of diagenesis by water rich in calcium carbonate occupying the interstices and subsequently precipitating sparitic calcite. This feature has considerable significance from the point of view of provenance rocks and the subsequent physico-chemical conditions responsible for the $CaCO_3$ precipitation. The various characteristics of this facies point to their being a product of stream flow deposits[58,93].

Trough Cross-Stratified Gravel Lithofacies-(Gt)—This lithofacies shows well developed trough foresets with shallow concave upward bounding surfaces, with a dip of about 10°-12° which upward becomes planar to horizontal. Gt-facies at places shows planar foresets which were eroded by later phase of deposition, marked by tangential relationship with planar and trough beds. The stratified Gt-facies shows typical fining upward interbeds of coarse and fine packages. The coarser bands are of 8-10 inches in thickness, and shows clustering along the beds. The clasts size ranges from 1 to 1.5 cm comprising mainly of granite, jasper, chert and flints, they are sub-rounded to rounded. The larger clasts showing clustering are mainly of carbonates and the size ranges between 2 to 2.5cm. The trough foresets are well developed where the lithounits attain its maximum thickness. This lithofacies is the product of sedimentation of a high flow regime. The erosive nature of the contact is indicative of high energy flow regime as well as represents lateral migration of bars with curved shallow channel scours or by minor shallow channel-fills[64,67]. As the trough axes of the foresets are taken as the channel orientation with high angle values of plane beds, suggests that these were deposited under bar morphology due to increase in channel gradient or were deposited by low sinuous channel under high energy flow[68]. The abundance of carbonate nodules points to, high deformational stress, and sudden change in flow regime and sedimentation pattern that could be attributed to tectonic factor. The concave upward base of trough beds, which shows vertical as well as lateral accretion indicate typical deposits of low-sinuosity channel morphology.

Sandy Gravel Sheet Facies-(Gs)—The gravelly sand occurs as a sheet like body (Fig. 36). It mainly comprises the carbonate and basaltic clasts. The grain size fines and becomes finer as coarse sand where it merges with the silts and clay assemblages. The Gs-facies occurs in association with the Gt-facies. But is more calcretized than that of the Gt-lithofacies. The gravelly sand sheet pinches out and merges into the fine sand, silts and clay sediments assemblages. The Gs-facies conforms its deposition over the channel margins. The greater compaction of Gs-facies suggests that during the shifting of the channel this portion was exposed to weathering and chemical precipitation earlier than that of the Gt-lithofacies.

Overbank Accretion Facies-(Fl)—The lithofacies occurs over the Gp-facies, owes its sedimentation by overbank deposition due to gradual vertical aggradation of

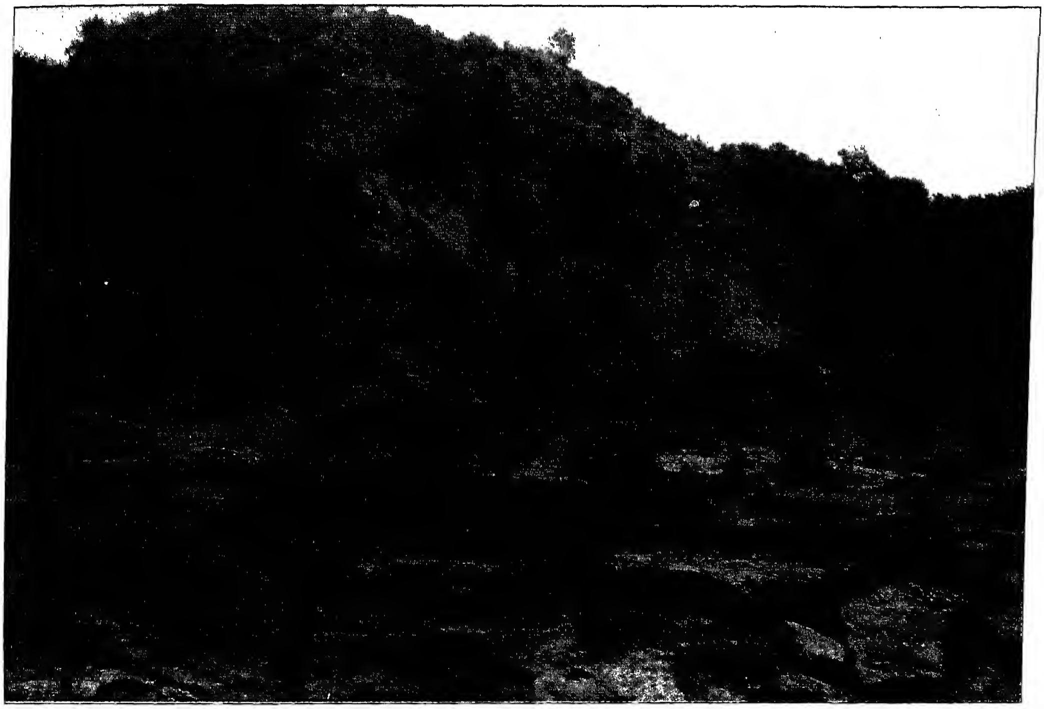


Fig.36 Sandy gravel sheet–Gs facies at Madhavghat

sediments from suspension following the flooding events, giving rise to alternate layers of sand, silt and clay[74,79]. The contact between Fl and Gp facies is slightly undulatory and at places erosive. The overall facies thickness varies from 3 to 4m. Calcrete bands act as an lithological boundaries, which could be products of fluctuating groundwater levels during the waning flood conditions. As the Fl-facies does not show any well developed pedogenic feature, it seems that the surface might not have remained exposed for long period to sub-aerial weathering and the vegetal growth, the latter fact is marked by low density of buried rootlets. This is overlain by a pedogenised mud horizon, whose thickness is not uniform, suggest an uneven topography over which the deposition of fine clay sediments had taken place. It is similar to the underlying basal pedogenised mud horizon (below the Gp-facies).

It is likely that the deposition of this facies took place over a flat to slightly scoured erosional surface of the underlying gravelly facies. The sediments are indicative of the margins of a huge longitudinal bar system and this facies points to a reduced energy system as compared to the processes responsible for the formation of the underlying lithofacies. The absence of coarse gravel units, the presence of sand, silt and mud reveals that the sedimentation took place through a fluvial form of intermittent flood deposits loosing energy after debouching from

the pediment zone of the foot-hills. The absence of pedogenetic features in this facies indicates rapid onset of aridity, leading to deposition of the overlying windblown material without any time gap of appropriate climatic conditions that would have brought about pedogenesis.

Planar Cross-Stratified Sand Facies-(Sp)—Development of this facies is intermittent, and is represented by a discontinuous horizon comprising lensoid bodies best seen in the middle reaches of the Sabarmati. On the basis of the grain size, it has been divided into three units. The formation is made up of a lowermost mud layer over which rests a coarse sandy layer which is topped by discontinuous gravel occurrences. Studies have shown that its main component is fine sand and coarse silt; the gravel is less prominent. This facies however, points to a reduced energy system as compared to the processes responsible for the formation of the underlying gravelly deposits. The absence of coarse gravel units, the presence of sand, silt and mud indicates that the sedimentation took place through a fluvial form of intermittent flood deposits loosing energy after debouching from the pediment zone of the foothills.

Palaeosols and Calcrete Layers Facies-(Pc)—The various horizons of buried soils representing this facies are well exposed all along the river valley and mark individual aggradational surface of various deposits, which remained exposed to sub-aerial weathering and then got buried by successive subsequent episodes of flood events. Each paleosol horizon shows differing colours and perhaps this variation is due to temporal differences of lithological and climatic factors during the deposition and the post-depositional diagenetic changes. These do not show any well developed 'O' and 'A' organic-bearing horizons. The grain-size data of the original sediments show following parameters: average mean grain-size ranging between 3. 5 to 4 phi, moderately sorted, platykurtic and coarse skewed to strongly coarse skewed. The red (rubified) soil occurs as a marker horizon, in which no colour variation is seen[94]. While the A-horizon is also absent, only the Bk-horizon is marked by accumulation of carbonate nodules (calcrete) and show high percentage of illuviated clay. The rubified sediments are typically fluvial; this is revealed by the textural characteristics[95]. These sediments are reddened by a subsequent pedogenetic process; the red colouration being due to the presence of finely divided ferric oxides, chiefly hematite and geothite. Formation and preservation of such red beds are supposed to occur only in relatively inactive or episodically active geomorphological environments. The rubified sediments thus indicate again a period of non-deposition and pedogenisation, prior to the onset of the next fluvial cycle.

The Quaternary sediments in the Sabarmati river basin point to their accumulation in an alluvial fan environment near the basin margin[94]. The alluvial

gravels owe their origin to the processes of debris and stream flows. The directional structures and downward and upward fining trends, establish the sediment path and the gravel lithofacies point to their accumulation in the proximal, medial and distal parts of the fan. The alluvial gravels vary in lithology and show a decrease in internal sedimentary structures down the fan. The later aggradational phases owe their origin to overbank deposition during which the rivers mainly transported sand and silt. The last aggradational phase was the usual aeolian deposition that shaped the present landscape of the Sabarmati basin.

Calcretes

Calcretes of the study area have been investigated and described briefly to provide appropriate background to the factor of climate in relation to the alternating periods of deposition and non-deposition. A most striking phenomena recorded in the sedimentary sequence is the occurrence of different varieties of calcretes at several horizons. A term synonymous with caliche[96,97] and 'Kankar'—a name prevalent in Indian literature. Calcrete represents a continental near surface accumulation of calcium carbonate formed by processes related to pedogenesis or evaporation/$CaCO_3$ saturated groundwater. They indicate processes such as replacement, and/or displacement and/or cementation. Though the precise genesis of calcrete is yet to be fully understood, but they are definitely indicators of climatic fluctuations—humid to semi-arid.

Calcretes are important in the role they play within the natural carbon cycle, with about 1700 gT being sequestered in soils as carbonate carbon[98]. Pedogenic calcretes reflect temporal maturity in their size; each size-class being related to the hierarchically lower class through an evolutionary morphogenetic sequence[99]. The most immature (conceptional stage) calcretes are powdery coatings (Stage 1 calcrete) which transforms through accretionary growth to 5 cm diameter concretions (Stage 3 calcrete). A total of six stages have been identified[99] Vadose zone calcretes have been explained by two contrasting models[100]. The 'per ascensum' model invokes precipitation through super-saturation of fluids rising due to capillary action. In the 'per descensum' model identical conditions are met through a progressive water loss during percolation.

Within the Quaternary sedimentary record of Mainland Gujarat, calcretes are observed associated in some form or the other with all deposits of the succession. However certain associations are distinctive and ubiquitous. These include:

a] Basal vertisol calcrete,

b] Calcretes associated with alluvium,

c] Calcrete gravels, and

d] Calcretes associated with aeolian dunes and related palaeosols.

Basal Vertisol Calcretes

At the base of sedimentary successions, in most localities a grey pedogenised horizon underlies planar cross-stratified gravels. The unit shows peds which are angular-blocky rendering the unit a fractured appearance. This horizon is rich in montmorillonite and illite clays and has a high shrink-swell capacity. Within the horizon there occur calcareous concretions ranging in size from 5cm to 12cm in diameter, show recrystallization and shrinkage features. Distended from the erosional contact between the gravel and the underlying pedogenised horizon are fissure related calcretes which are spaced in a systematic fashion. The fissures are straight to slightly sinuous planes 1-3cm thick along which calcium carbonate has precipitated. Rhizoliths too are observed in this and are commonly 1-4cm in diameter. Also observed are bluish drab haloes[101] surrounding root remnants.

Slickensided argillans (stress cutans) have developed owing to the preferred directional orientation of the clay minerals during heaving and shrinking of the soil. The slickensides and associated carbonate impregnated fissures convey typical vertisol characteristics[102-103] (Fig. 37). The fissures indicate events of extreme drying whereas the slickensides formed due to episodic shrinking and swelling of the clays in tandem with fluctuating moisture levels in the soil. Such fluctuations are directly related to a seasonal climate.

Fig. 37 Basal vertisol calcrete showing fissures and overlain by calcrete gravel at Rayka

Calcretes Developed in Alluvial Deposits

Calcium carbonate impregnation's along bedding planes of channel fill deposits and mid-channel gravel bars are observed at numerous sites. They show varying degree of maturity from insipid cement to 3-5cm nodules. The sandy carbonate nodules coalesce to form larger aggregates in the channel fill sands. At places, the carbonate appears to have displaced the original sand matrix to form carbonate rich orthic nodules. The disposition of calcium carbonate along bedding planes

gives rise to a layered appearance. At many places the layers have large root casts up to 1m in length and 4cm in diameter. The root casts extend vertically down for some distance and then at certain levels spread laterally to form a mat of rhizoliths.

These calcretes appear to be the result of groundwater (sub-surface) movement along bedding planes. Precipitation of carbonate might have initially taken place as a cement and then progressively with time due to the displacive action of calcite grew into concretions[104]. The large root casts are of phreatophytes which tapped the then existing water table. The root casts have typical microfabrics[105-108]. There is a central zone of dense micrite often referred to as clotted micrite. Around this zone there is a progressive increase in the detrital components which is mostly quartz. Most of the quartz grains show corroded boundaries, an indication of the replacive action of carbonate and also exhibit circum-granular calcite in the form of micrite as well as fibres of calcite. Needle-fibre calcite is also observed associated with (alveolar structural veins left by rootlets and later filled by carbonate).

Calcrete occurrence in overbank floodplain deposits on left bank of Narmada near Jhagadia, are peculiar (Fig. 38). Here the calcretes occur as disorthic nodules disposed in parallel bands which show a broad conformity with the geomorphic surface. The bands are spaced generally 10-15cm apart. The calcrete nodules which are commonly 3-5cm in diameter, show an initial event of micrite precipitation, evidence of replacive action of calcite which is then followed by cracking, related to shrinkage. These cracks have been later filled up by sparry calcite. B fabrics such as needle fibre calcite and alveolar septal structure too are observed. While

Fig.38 Banded pedogenic calcretes developed in alluvium at Jhagadia

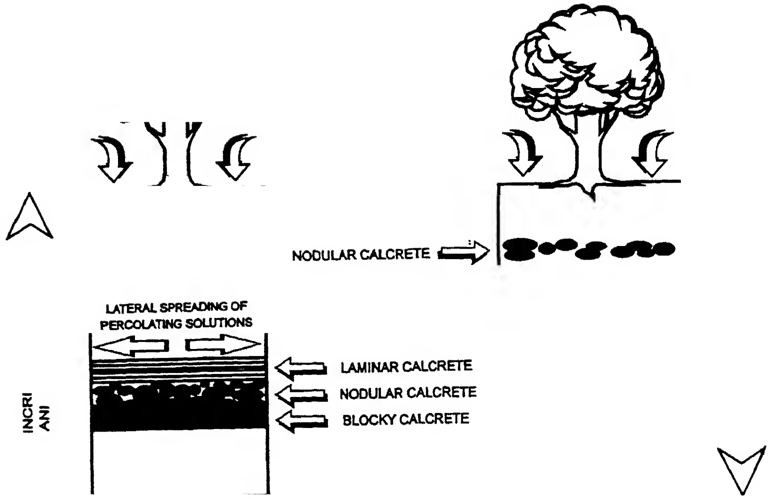


Fig.39 Model for banded calcrete formation

such calcretes may be attributed to floodplain accretion, there is field evidence for only two major floodplain accretion events, though the number of bands is seven. These calcretes represent a product of pedogenesis, and are interpreted as documenting a falling mean annual rainfall. This could be inferred because the depth to which the soil carbonate forms a K-horizon is directly related to precipitation. The inverse interpretation (increasing mean annual rainfall) is untenable owing to the fact that the first carbonate horizon would have acted as an obstruction to the leachates, and the result would have been a massive bouldery calcrete (Fig. 39)

Calcrete Gravel

In the Mahi river basin, some of the coarser stratigraphic levels are represented by planar cross stratified gravel in which the primary clast component is that of calcrete nodules (Fig. 37). The dissolution of these clasts has releases carbonate which migrates in the matrix of the gravel and reprecipitates as cement. Due to this cementation these gravel horizons are typically well indurated and almost conglomeratic. Such calcrete conglomerates have been described before from arid river systems[109]. These units indicate the excavation of banks in which calcretization had progressed to either stage III or where groundwater calcretes were in abundance. Such released nodules, are entrained as bed load and re-deposited as mid-channel bars further downstream within a short distance span (Fig. 40).

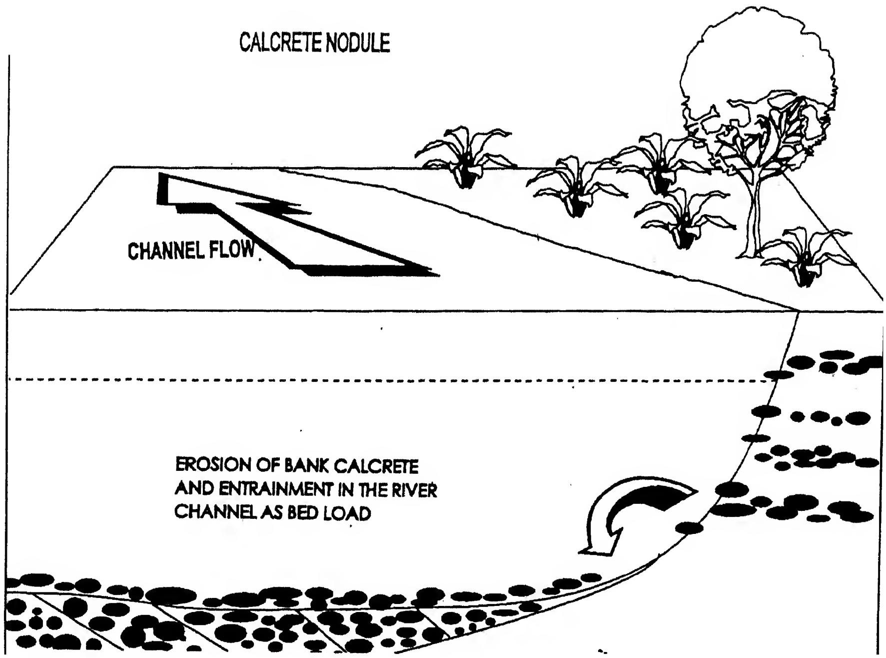


Fig.40 Formation of calcrete gravel through erosion of banks

Calcretes Developed in Aeolian Dunes and Related Palaeosols

Within the aeolian dunal component of the stratigraphic successions (at Rayka, Mahudi, Poicha, etc.), horizontal bands of nodular carbonate are observed. The carbonate nodules have a diffused boundary with the surrounding sediment (i.e. it is orthic in nature). There are also instances where the nodular bands are connected through vertical discordant nodules. The nodules themselves are impure, having a considerable clastic component in them. Elsewhere rhizoconcretionary carbonate pipes occur in association with palaeosols. These root-casts are commonly less than a centimetre in diameter and are short sinuous tube like structures. Carbonized root remnants are also observed within the palaeosol.

The horizontal bands of carbonate which occur independent of soil formation imply that the phase of dune stabilization was not prolonged. However the nodules in themselves suggest a period of non aggradation during which precipitation was channelized along stratification planes. Precipitation of carbonate took place through super saturation of downward migrating groundwaters. These nodules thus may be classified as groundwater calcretes. The rhizoliths which are observed with palaeosol horizons reflect a desert shrub vegetation, which dominated the topography during periods of stabilization.

Palaeoclimatic Aspects

Characteristics of the exposed river sequences reveal an interesting late Quaternary paleoclimatic history, and the successive events of deposition, both fluvial and aeolian, punctuated by periods of non-deposition and pedogenetic changes, throw considerable light on the climatic changes that played their due roles in depositional processes and pedogenesis. Climates ranging from humid through semi-arid to arid have left their imprints in the sediments at various stratigraphic levels. Although it has been found somewhat difficult to precisely fix the dates of the climatic variations vis-a-vis depositional history and subsequent changes, a broad chronology of events has been worked out which quite clearly brings out the control exercised by various types of climate.

The factor of climatic control has been studied and analysed with three assumptions : viz. *(i)* High (strong) fluvial action was related to sub-humid to humid phases. *(ii)* Breaks in the deposition and subsequent exposure of the sediments to sub-aerial processes (development of pedogenesis, calcretisation etc.) have been considered as indicative of semi-arid climate and *(iii)* The aeolian silt deposits typically represent period of aridity.

It is however not very clear how exactly the global sea-level curves and related climatic variations in terms of warm-humid and cold-arid are reflected in comparable climate conditions in the sub-tropical areas. Perhaps periods of low sea-level synchronized with arid, semi-arid phases, whereas the progressive withdrawal of a transgressive sea marked increased fluvial activity.

Palaeoclimatic Sequence

A generalised picture of the succession of climatic changes during the deposition of the entire exposed sequence has been prepared by taking into account the— *(i)* integrated stratigraphic sequence, *(ii)* sedimentary structures, *(iii)* granulometry and *(iv)* repetitive events of pedogenic changes (development of paleosols, calcretes, rubification of silts and stabilisation of dunal sands). The climatic variation has been worked out on the basis of following assumptions:

1. Strong fluvial activity was confined to humid to sub-humid phases.
2. Pedogenetic changes are indicative of a sub-humid to semi-arid climate, on account of the action of sub-aerial processes during non-deposition.
3. Arid phase was responsible for the widespread deposition of wind blown sands and silts. (It is presumed that the aeolian silts and sands essentially comprised fluvial sediments reworked by wind action during the arid phase).
4. Amelioration of aridity and some increase in humidity was primarily responsible for the phenomenon of stabilisation of the aeolian sediments and pedogenesis all over the study area (and also to its south upto Central Gujarat and in the north upto South Rajasthan).

5. The present day climate though by and large, semi-arid to arid is characterized by fluctuating dry and wet spells.

N. Gujarat and S. Rajasthan today experience long spells of dry climate broken periodically by reasonably heavy rainfalls at intervals of a few years. A paleoclimatic sequence is suggested in Table VII.

Influence and Control of Climatic Factor

Before the onset of the first fluvial cycle, the basal clay horizon was exposed to sub-aerial processes bringing about some pedogenetic changes mainly calcretisation. This presupposes withdrawal of the Middle Pleistocene high sea, (prior to the onset of fluvial sedimentation) thereby exposing the tidal muds and silts to the action of atmospheric agencies. Calcretisation of the mud is ideally seen in the form of tubes, veins and strings of calcrete criss-crossing the clay horizon. The phenomenon of mottling (ferric to ferrous) could also be indicative of the effect

Table VII Generalised palaeoclimatic sequence

Semi-arid to arid	Present day unconsolidated sand, sand-sheets and dunes	Sub-recent to Recent (Upper Holocene)
Sub-humid to Semi-arid	Stabilisation and pedogenisation of aeolian silts and sands, Paleosol formation, development of calcretes and some vegetal growth on the dune surfaces	Middle Holocene
Arid	Aeolian silt and fine sand accumulations as a more or less continuous cover showing typical dunal morphology	Lower Holocene to Terminal Pleistocene
Sub-humid to Humid	Deposition of sediments of third fluvial cycle	Upper
Sub-humid to Semi-arid	Pedogenetic changes including rubification of the fluvial silts (Upper most beds of the second fluvial cycle) and development of calcrete in the silt horizon	Pleistocene
Humid	Desposition of sediments of second fluvial cycle	Upper
Sub-humid to Semi-arid	Pedogenesis of the upper part of the fluvial sequence including calcretization (of fractured mud layers)	Middle
Humid	Deposition of sediments of first fluvial cycle	Pleistocene
Semi-arid	Pedogenetic changes of the basal mottled bluish green clays (including calcretization)	Middle
Humid	Deposition of marine clays during a period of transgression	Pleistocene

of sub-aerial processes. The entire phenomenon of sub-aerial changes is an indication of time interval before the fluvial material started being deposited with the onset of humid phase and this could be taken as an evidence of a climatic change, pointing to increased rainfall and concomitant fluvial activity.

The main bulk of the fluvial sedimentation comprised two cycles of deposition, the material having been brought and deposited in two instalments. Each starting with a gravel and fining upward. An intervening period of non-deposition and some pedogenetic changes separates the two cycles. It was during this interval that the fractured mud of the earliest cycle was weakly pedogenised and gave rise to development of calcrete tubes and strings interspersed within the mud horizon. The second cycle is indicative of a rejuvenation of the fluvial regime which has been taken as an indication of return of humidity.

The rubified silts in all the river valleys which form the uppermost part of the second fluvial cycle, are strikingly different from the underlying laminated mud. The junction is quite well defined and the entire thickness is more or less silty and conspicuously reddened. Obviously the silty horizon marks the termination of the second fluvial activity. The rubification is typically a phenomenon related to the period of non-deposition with pedogenic changes brought about by sub-aerial processes during the semi-arid phase that followed.

The rubified horizon is followed upward by another major fluvial cycle of deposition, which indicates onset of a wet phase. Interestingly this fluvial sequence shows an upward coarsening, from a muddy bottom horizon through sand to the gravelly upper part. Such a sequence points to a progressive increase in the depositional energy and is in contrast with the earlier two fluvial cycles which show coarsening upward, gravel to mud/silt. This third fluvial cycle with the topmost portion being gravelly, appears to have been terminated abruptly by a sudden onset of aridity which brought to an end the fluvial deposition. It is interesting however to note that there was little appreciable time gap between the deposition related to the two climatic events, humid followed by arid, because the top of the fluvial deposits does not show any evidence of sub-aerial processes prior to the aeolian deposition.

The phase of high aridity that followed was responsible for the accumulation of extensive aeolian deposits, referred to also as aeolian silts (also referred to as loessic silts) marks a major global paleoclimatic event and has been recognised in most parts of the world. This aridity synchronized with a very low sea-level, the fall having been of the order of 120m. It represents the last major arid phase (LGM) of the late Quaternary. The aeolian sediments deposited during this phase form a more or less continuous blanket, the upper part of which is conspicuously stabilised. The present day hummocky and undulating topography, shows stabilization of this aeolian horizon, and points to some increase in humidity, the last paleoclimatic event. The phenomena of stabilisation and extensive calcretisation of the aeolian material is attributed to the change over to a semi-

arid/sub-humid phase which marked the end of aridity and synchronized with the rise of the Holocene sea-level. Since the advent of the phase of increased humidity till present day, the climate has been fluctuating between arid and sub-humid, thereby giving rise to the existing scenario consisting of a combination of shifting sands and partial stabilisation from time to time depending upon the periodicity of the climatic variations.

Chronology of Palaeoclimatic Events

The chronology of paleoclimatic changes, a phenomenon related to successive comparable glacial and interglacial events of the Quaternary is not fully established, especially for the Lower and Middle Pleistocene. Information for the Upper Pleistocene only is available and on the basis of indirect evidences like the nature of variation in the sediments (fluvial/aeolian), climatic sequences inferred from the foraminifera of deep sea cores and a number of sea-level curves (the rise and fall of sea-level indicative of warm and cold climate respectively), a tentative chronology and broad dates and durations of humid, semi-arid and arid climatic phases can be obtained. But the sequence of climatic fluctuations of the Holocene beginning with the Terminal Pleistocene aridity is better documented. In the Indian context too, this is true and the available data from North Gujarat and southwest Rajasthan and southern Rajasthan provides a reasonably good picture of the Holocene climatic fluctuations.

Pleistocene

Palaeoclimatic regime for the major part of the Pleistocene is not yet fully understood. Based on the classical concepts of the Pleistocene glacial and interglacial stages in the Alpine region, the Pleistocene epoch was divided into four glacials (Gunz (G)-Glacial I, Mindel (M)-Glacial II, Riss (R)-Glacial III and Wurm (W)-Glacial IV) and the intervening warmer interglacials (G/M, M/R and R/W); M/R was a period of great interglacial, while the R/W was a period of last interglacial. The last glacial synchronized with the 2000 years BP aridity and the Holocene warming forming the post glacial stage.

Zeuner[110] and Fairbridge[111] attempted to correlate the interglacial stages with various high sea-levels of the Quaternary. A progressive falling of transgressive strandline during the periods of interglacial sea-level rise, postulated by these workers is now not accepted. But then, none of the subsequent studies has offered convincing alternative sea levels for major part of the early Quaternary, and details of sea levels and related climatic fluctuations till the advent of Middle Pleistocene are not available. In this connection the works of Milankovitch[112], Emiliani[113], Ericsson[114] and Chappel and Shackleton[115] do provide some information on Quaternary sea levels and palaeoclimates but as will be seen in Fig. 41, their postulations differ in respect of ages and durations.

The main bulk of the fluvial sequence of the area of investigation which broadly belongs to Middle and Upper Pleistocene, falls within the last interglacial stage and the successive fluvial cycles perhaps indicate climatic fluctuations within the main interglacial stage. The entire fluvial sequence which is resting over the bluish marine clays, which according to Merh[39] represents the high sea-level of the Middle Pleistocene, appears to have been deposited in the course of 200 to 240 KY ago.

The sea-level curve of Chappel and Shackleton[115], (Fig. 41) shows almost 150m fall of sea-level around periods of extreme aridity (glaciation in Polar areas).

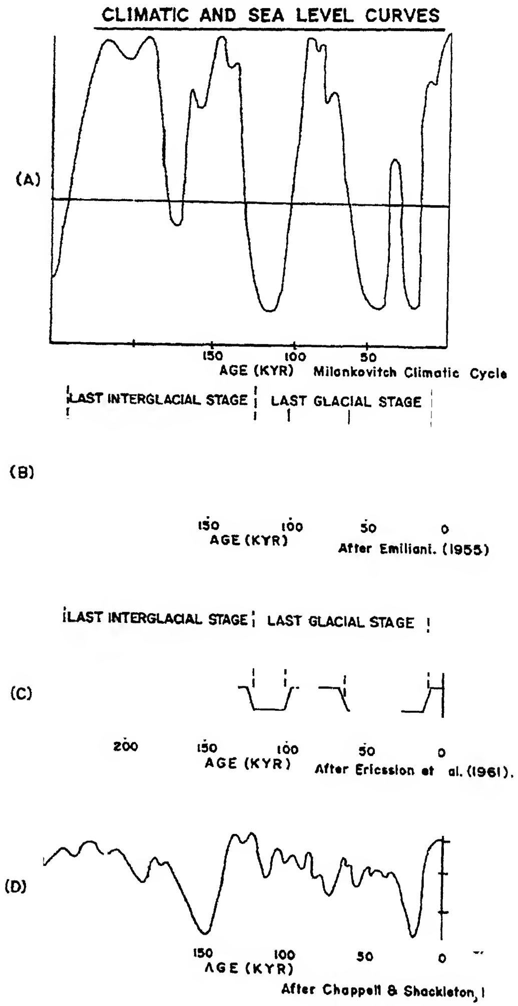


Fig.41 Palaeoclimatic and sea-level curves[110-112]

The intervening periods of high sea level could be taken to synchronize with the humid phases of fluvial activity. The high sea-level of the Middle Pleistocene dated around 240KY, must have progressively gone down, of course with minor fluctuations and it is quite logical to surmise that it was during this period of high sea level and wet climate that the oldest formation was deposited in two instalments. The main part of the fluvial sedimentation comprised two cycles of deposition, the material having been deposited in two instalments, each starting with a basal gravel and fining upward.

The climatic changes at the close of the deposition of Hirpura formation (Sabarmati), Dabka member of Shihora formation, (Mahi) and Ambali formation (Narmada), which brought about the pedogenesis of the upper mud horizon could be interpreted as a minor period of non-deposition and semi-aridity. At present there is no conclusive date to fix this event, but considering various sea-level curves and assuming the fall of sea level with increase in aridity, this event of non-deposition and pedogenetic changes could be anywhere around 180 KY.

The lowermost gravel shows considerable compaction and is almost rock like; it has been reported to contain Lower Paleolithic tools in the Sabarmati valley[5]. Subbarao[115], recorded Lower Paleolithic tools from the comparable gravel of Mahi. According to Pant and Chamyal[19], the Lower Paleolithic culture in Gujarat must have flourished around 200Ky. BP, and they suggested that in the Mahi the lowermost gravel and the underlying clay deposits might be older than 200KY. Baskaran et al.[117] discovered Lower and Middle Paleolithic tools in the fluvial gravels underneath the miliolites of Hiran Valley in south Saurashtra; and they dated them around 190KY. Recently, Sareen *et al.*[31], have dated this gravel horizon (using TL technique) in the Sabarmati valley to be less than 300KY. Although it is not at all possible to precisely fix the age of these gravels, it is most likely that they could be belonging to an age ranging between 200-240KY.

Taking into account the global climatic changes and sea level curve of Chappel and Shackleton[115], the date of the second fluvial cycle has been tentatively fixed. An approximate age for the cycle could be assigned from 160-140KY. The rubification of the overlying silts is attributed to the semi-arid phase, during which sub-aerial exposure and reddening of the silty sediments and calcretisation took place. This event of non-deposition and sub-aerial weathering can broadly be dated to, at the maximum around 140KY. The fluvial cycle resting over the rubified silts starting with mud and coarsening upward perhaps represents the closing period of last interglacial and its duration can tentatively be fixed from 130KY to 20KY i.e. the termination of the Pleistocene. An interesting feature of this formation is the coarsening upward of the grain size-mud to sand to gravel, indicating a progressively increasing depositional energy conditions towards the end of the cycle. An abrupt end of fluvial deposition and sudden change from wet to dry climatic conditions is envisaged at the boundary of this fluvial cycle. The contact between the fluvial sediments and the overlying aeolian silt is quite sharp and

does not provide any indication of time gap or climatic event during which pedogenetic changes could have occurred. This sudden change in climate and the advent of the main arid phase marks the termination of the Pleistocene period. The arid phase synchronizes well with the low sea-level (of the order of–150 to-120m). This event is well documented and can be put anywhere around 20,000-18,000BP. This climatic change at the termination of Pleistocene preceeded the advent of Holocene.

Holocene

The Holocene epoch comprising approximately the last 10,000 years of the geological record can, in the study area be broadly divided into four main climatic phases. *(i)* The earliest part of the Holocene witnessed the continuation of the Terminal Pleistocene aridity. This dry climate marked by strong aeolian action gave rise to loess-like aeolian silt accumulations (sheets and dunes) all over North Gujarat and south Rajasthan. *(ii)* A semi-arid phase followed during which the stabilisation of the aeolian sediments took place. This phase brought about conspicuous pedogenesis and profuse development of calcrete. *(iii)* A brief arid phase of comparatively short duration came next and to this phase could be attributed the salinity of the Rajasthan lakes and development of playas. *(iv)* The last climatic event is the advent of the present day sub-humid to semi-arid climate.

The alternating climatic sequence viz. arid-humid-arid-humid in the course of last 10,000 years are also revealed in the sediment record and can also be recognised in numerous features viz. aeolian deposits as sheets and dunes, stabilisation, pedogenisation and calcretisation of the aeolian deposits, sporadic occurrence of second generation dunal material and its subsequent partial pedogenisation and local development of fluvial deposits as flood plains.

The precise durations of the various climatic phases and their chronological/absolute ages are still the subject matter of considerable debate and numerous workers[9, 18, 118-122], who have investigated Holocenes of South Rajasthan have presented somewhat conflicting details though agreeing in the overall sequence of changes in the events. Table VIII summarizes the conclusions arrived at by these workers.

An Overview

The significance of Quaternary period lies in the interesting combinations of glacio-eustastic sea-level fluctuations, related climatic variations and tectonic activity, and all these have been faithfully recorded in the non-marine sequences of Gujarat. Various facets of the continental record of the Mainland have been described and an attempt has been made to integrate the different parameters and processes responsible for their deposition (Fig. 42). The results of the investigations have amply established that the entire phenomenon of deposition was essentially

Table VIII *Chronology of climatic changes since 18 Ky BP*

Age Years BP \ Workers	Singh *et al.* (1972)	Singh *et al.* (1974)	Allchin *et al.* (1978)	Bryson & Swain (1981)	Singhvi *et al.* (1982)	Swain *et al.* (1983)	Rajaguru (1983)	Wassan *et al.* (1983)	Mishra *et al.* (1988)	Sharma & Chauhan (1991)	Dhir *et al.* (1994)	Singhvi *et al.* (1994)
Present – 1000	Salinty of lakes	Present day conditions		Wet phase (700-1100)				Present day		Marine inundations		
1000 – 3000		Increase in rainfall exclusively dry 1500-1800 BP)		Aridity at 2000-3000 BP). Lakes become saline and dry up at 3700 BP		Lakes start drying. Salinity of 3700 BP		Very arid (3000-1700) drying of lakes of 4000 BP.		Aridity and salinity of lakes (3700 BP)	Aridity and drying of lakes	
3000 – 5000		Aridity increases at 4000 BP. Lakesdry up and salinity increases	Aridity	Wettest Phase of last 10000 years		Wet phase upto 3700 BP	Wet phase upto 4000 BP	Wettest phase	Marked Sub-humid wet climate (4000-10000 BP)	Wet phase	High water level	
5000 – 9500		Wet phase at 5000 BP. Punctuated by minor changes at 8300		Wet phase cultivation seen. Readvance of glaciers of 8300 yrs BP.				Lacushine conditions			Moist Phase	
9500 – 10000	Sudden end to arid phase	Semi-arid sand dunes start to stabilise. Fresh water conditions	Fresh water conditions			Fresh water conditions. Lakes start filling up. Dunes stabilise						
10000 – 18000	Aridity, Aeolian activity widespread	Major aridity choking up of valleys, inland lakes formed	Major dry phase. Dunes extended over everywhere	Major aridity monsoons supressed.	Major aridity Dune activity starts from around 20000 BP.	Extreme aridity; Sand dunes formed. Choking of valleys. Inland lakes formed.	Aridity between (15000-25000 ka)	Major aridly Hypersaline conditions	Distinct dry climate during Terminal Pleistocene	Extreme aridly. Dune formations. Lakes/ Basins formed	Extreme aridity	Dune building activity (15-25 ka)

controlled by the factors of neotectonism and palaeoclimate. The site of sediment accumulation was the Cambay Basin tectonic depression, filled by Tertiary sediments, over which were deposited the Quaternary sediments. The Cambay Basin from the very beginning was dissected into a number of tectonically active sub-basins and the total quantities of Tertiary and Quaternary sediments in the various sub-basins were different. As a result, the Quaternary record shows a marked variation in thickness ranging from 100 to 800m. The role of tectonic factor in sedimentation is manifested in pre, -syn- and post-depositional movements along numerous basement fracture trends. The behaviour of Cambay Basin sub-blocks, and the variable thicknesses of sediments, the complex drainage pattern and the overall topography, typically point to the importance of neotectonic activity all throughout the evolution of the Quaternary terrain.

The continental sediments, dominantly fluvial, of the Mainland Gujarat owe their origin to a succession of depositional events with intervening periods of non-deposition and subaerial weathering. Thus the stratigraphic record is

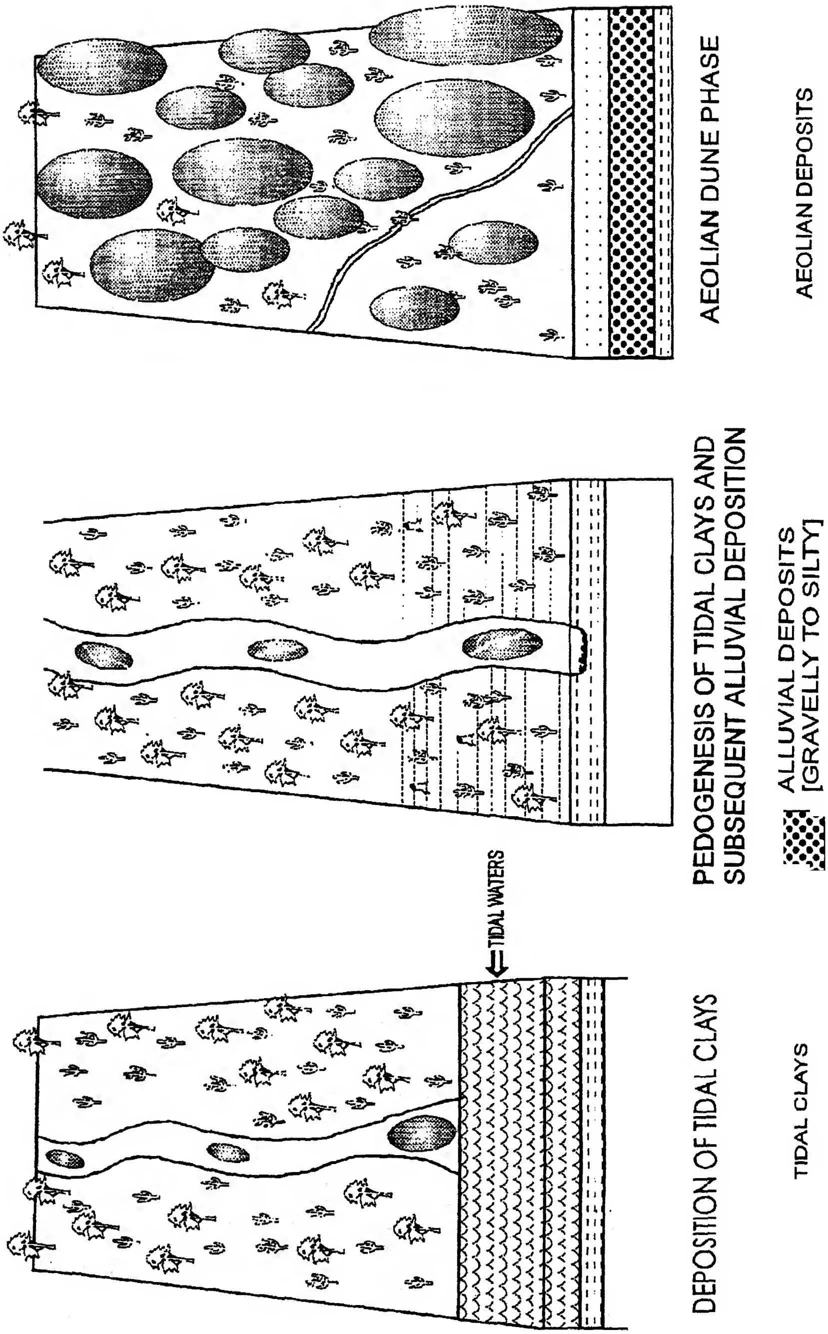


Fig.42 Cartoon showing successive phases of aggradation through different depositional systems

represented by a succession of sediments belonging to at least three fluvial cycles (Table IX)—two lower ones being quite prominent. The nature of sediment sequence in the three fluvial cycles, reveals much. Whereas in the two older cycles, the sediments show the usual fining upward, starting with gravel and ending with fine sand/silt, in the case of the third cycle, it started depositing sand first and ended up finally with the gravel at the top, thereby pointing to a progressive increase in the energy conditions, unlike the earlier two cycles.

The study has revealed that the entire deposition took place during Upper Quaternary by a drainage system which was quite different from the one seen to-day. Main bulk of the deposition was brought about by numerous rivers that flowed into the Cambay Basin depression, followed ENE-WSW to NE-SW courses

Table IX Synoptic view of geological history of the alluvial plains

EVENTS	ENVIRONMENT	ENERGY CONDITIONS	LITHOLOGY	PEDOGENESIS	CLIMATE
Deposition of present day unconsolidated sand-sheets and dunes		Moderate to low	Sand and silt		Semi-arid to arid
Deposition of dunal sands	Aeolian environment	High velocity winds	Sand and silt		Arid
Period of non deposition	Sub-aerial weathering			Stabilization and pedogenisation of silts. Palaeosol formation and calcretization	Sub-humid to Semi-arid
Sudden deposition of sediments of silt and fine sand	Aeolian	High velocity winds	Fine to medium grained silts and coarse sand		Arid
Deposition of third fluvial cycle	Fluvial environment	Reduced energy conditions Deposition in the form of intermittent flash floods	Mud, coarse sand and lenses of gravel, chiefly composed of quartz grains, feldspars and micas		Sub-humid to humid
Period of non deposition	Sub-aerial weathering			Pedogenetic changes including rubification of silts and development of calcrete nodules at the base	Sub-humid to semi-arid
Continuing deposition of second fluvial cycle	Fluvial environment	Moderate to low energy conditions.	Silts and sands		
Deposition of second fluvial cycle		High to shallow energy cionditions	Gravel comprising of varying sizes of quartzite, rock fragments capped by mud		Humid
Period of non deposition	Weak sub-aerial weathering			Weak pedogenesis of the top part (mud)	Sub-humid to semi-arid
Deposition of first fluvial cycle	Fluvial environment	High to shallow energy conditions	Gravels comprising clasts of quartzite, granite, chert jasper and rock fragments overlain by mud		Humid
Period of non deposition	Sub-aerial weathering			Pedogenetic changes in basal clay	Semi-arid
Marine conditions (High sea)	Tidal environment	Low energy	Clay rich in illite, smectite, montmorillonite and silt comprising mainly quartz, feldspar and micas		Humid

and finally impinged into the ancestral Arabian Sea. This drainage was essentially slope controlled, though some fracture lineaments might have partially influenced its behaviour and depositional pattern. This early drainage was considerably modified during Holocene such that some rivers (Sabarmati, Mahi) started flowing along new courses and others, survived only as relicts or as very insignificant streams (Fig. 43). This disruption of earlier drainage by superimposition of a new one was entirely a tectonic phenomenon, related to the development of NNE-SSW fractures. The fluvial regime of the area thus comprises an early stage of deposition brought about by a drainage system in several instalments, followed by a late stage during which the main depositional activity came to a close, courses of the earlier rivers were disrupted, and partially modified, and the earlier deposited sequences were exposed along the newly formed cliffs.

By and large, the fluvial activity synchronised with the humid/wet climatic phases whereas the depositional breaks indicate cessation of fluvial activity either due to climatic change or tectonic activity in the provenance. Though it is rather difficult to distinguish precisely the actual cause, it is quite logical to invoke a break in deposition due to climatic change (humid to semi-arid) where the exposed surface was subjected to sub-aerial agencies to bring about pedogenetic changes and calcretization. On the other hand, where the break is abrupt and does not involve role of climate in the sediment modification, the possibility of tectonic factor causing stoppage of deposition could not be ruled out. This tectonism might have influenced the provenance or it might have affected the strandline which in turn would bring about a pause in deposition. Nothing can be conclusively stated without further in-depth studies on this aspect.

Four prominent palaeosol horizons indicating subaerial weathering are recorded. The earliest pedogenised surface is that of the basal clays with abundant calcrete formation. The next one upward is that of the upper part of the silt that overlies the gravel (G-I). This is typically indicated by a distinct fractured appearance of silts and abundance of calcrete. The third event is that of rubified silt which forms the top of the second fluvial cycle. The conspicuous reddening and extensive development of calcrete are the characteristic and diagnostic features of the pedogenesis of this horizon. The last major pedogenetic event is seen in the stabilisation of the dunal sand and silt; the pedogenetic changes and calcretization represented drier climate, pointing to semi-aridity. Extreme arid conditions are indicated above the fluvial sequence. Subsequent stabilisation of the topmost aeolian horizon is indicative of amelioration of climate and increased humidity in the atmosphere, adequate enough to bring about stabilisation of the dunal sediments.

An interesting fact worth highlighting is the phenomenon of calcrete formation at various levels which shows a slightly different story. Whereas all the pedogenetic surfaces are invariably accompanied by calcrete formations, quite a few calcrete horizons, especially the layered ones in the lower parts of the silts of the first

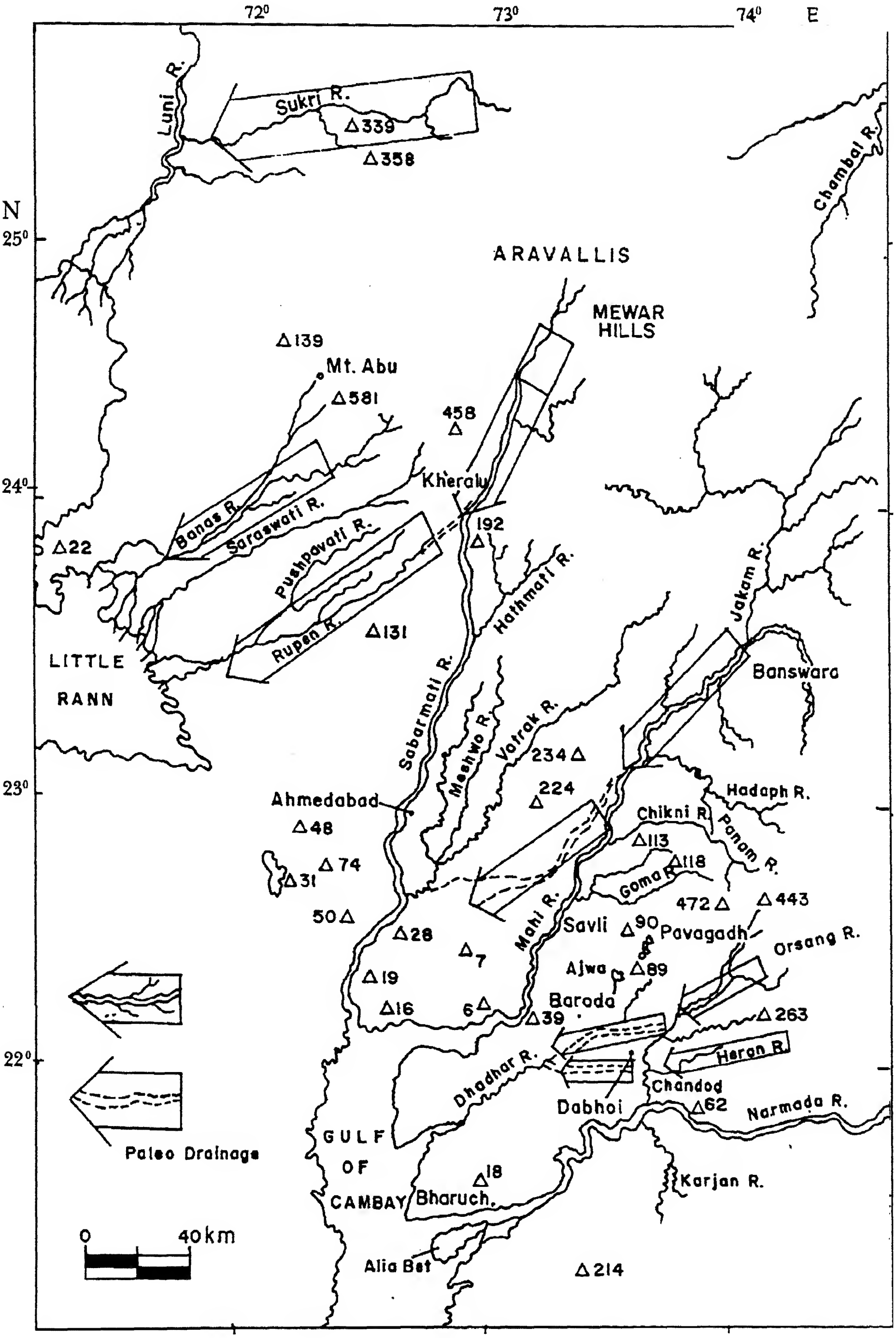


Fig.43 Former and present day stream courses. Arrows show the reaches of the disrupted ancient drainage.

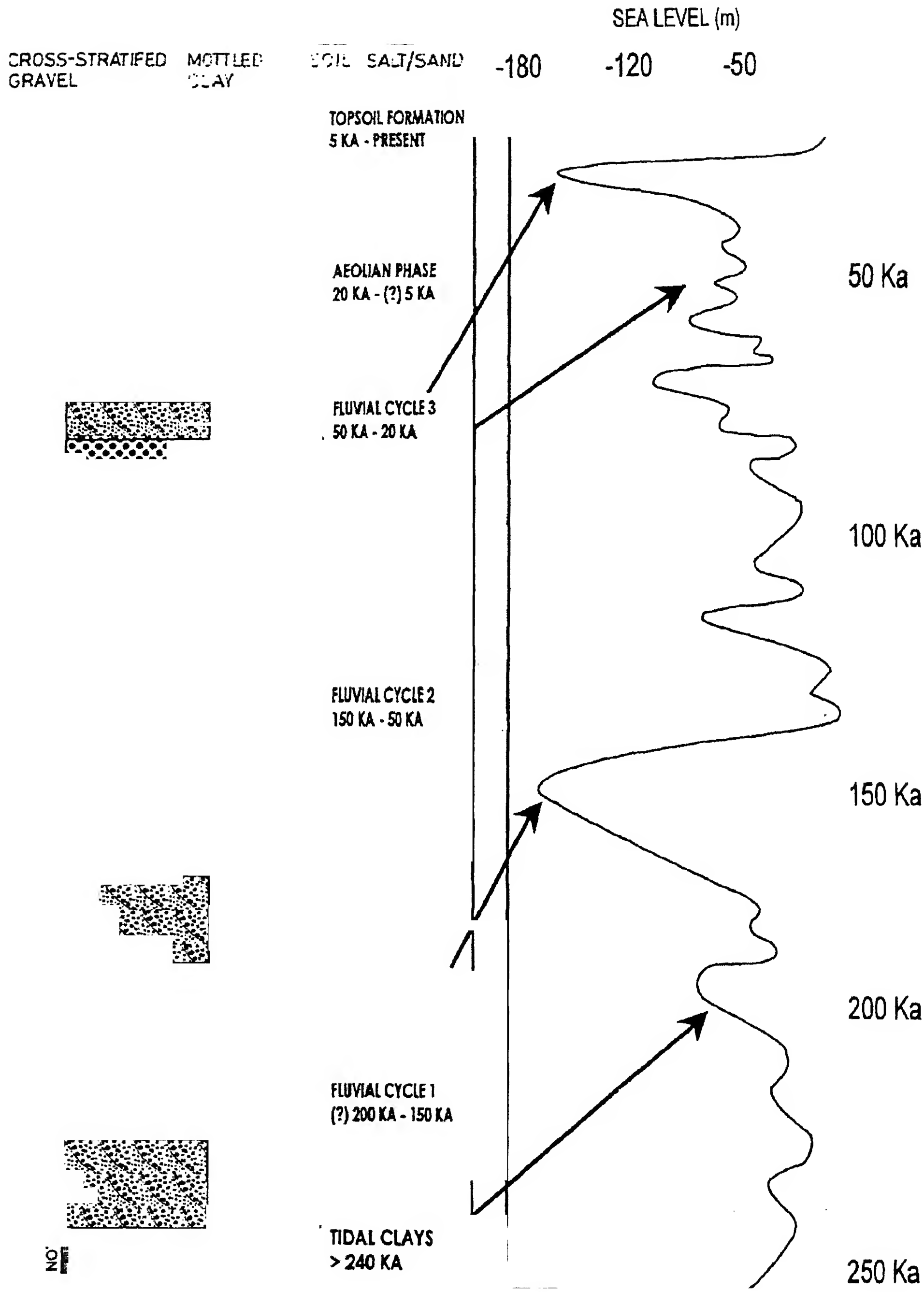


Fig. 44 Relationship between global climatic changes (based on sea-level curve[115]) and fluvial cycles.

fluvial cycle and in the laminated sands of the second fluvial cycle are unrelated to pedogenesis; instead they characteristically point to their being valley calcretes, a variety represented by the precipitation of calcium carbonate due to progressive drying up of river channel. Laminar calcretes in dunal sands on the other hand, point to aperiodic fluctuations in the rainfall intensity.

The post-aridity climate of the Holocene recorded in the dunal sediments indicate a succession of minor climatic fluctuations between arid and sub-humid, which are ideally reflected in the numerous palaeosol and calcrete horizons within the dunal sands.

Though an attempt has been made to work out a sequence of depositional events with breaks and periods of non deposition, with or without pedogenesis, it has not been possible to obtain precise durations of the various events because of the absence of absolute radiometric/TL dates for key horizons. The processes of erosion, deposition, weathering and pedogenesis, were all closely related to the palaeoclimatic factors of rainfall, humidity and temperature. Presuming that climatic changes were reflected in the global sea-levels a broad correlation has been established between the transgressive-regressive strandlines and the arid-humid climatic phases (Fig. 44). In the tropics and sub-tropics the low sea level would synchronise with aridity and a high transgressive sea would point to a wet climate. There were however fewer variations in temperature, and perhaps both wet and dry phases were relatively warm. Rock weathering and pedogenetic processes took place under such climatic conditions. A better and more clearer picture will emerge when exact ages of sediments at successive horizons are available.

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